No. 1 1946

THE JOURNAL
OF THE
IRON AND STEEL INSTITUTE

Vol. CLIII

EDITOR

K. HEADLAM-MORLEY

SECRETARY

ASSISTANT EDITOR

A. E. CHATTIN, B.Sc., (Hons. Met.), A.R.I.C., F.I.M.

ASSISTANT SECRETARY

PUBLISHED AT THE OFFICES OF THE INSTITUTE
4, GROSVENOR GARDENS, LONDON, S.W.1.
1946

LIST OF THE COUNCIL AND OFFICERS

as at 12th March, 1947.

President: Cecil H. Desch, D.Sc., Ph.D., F.R.S.

Past-Presidents.

Sir Frederick Mills, Bt.
Sir W. Peter Rylands, Bt.
Benjamin Talbot.
Col. Sir W. Charles Wright, Bt., G.B.E., C.B.
The Rt. Hon. the Earl of Dudley, M.C.
Sir John Craig, C.B.E., D.L.
Arthur Dorman.

Hon. Treasurer.

The Hon. R. G. Lytellton.

Vice-Presidents.

Capt. H. Leighton Davies, C.B.E.
Wilfred John Dawson.
Gustavus Henry Latham.
Andrew McCance, D.Sc., F.R.S.
Richard Mather.
James Robert Menzies-Wilson.
James Mitchell.

Hon. Vice-Presidents.

The Rt. Hon. Lord Airedale of Gledhow, D.S.O., M.C.
Carl A. F. Benedicks, Ph.D.
William J. Brooke.
Sir Peter Boswell Brown.
Alfonso de Churruca.
Fred Clements.
Edmund John Fox.
Sir Edward J. George.
Lieut.-Col. Sir John Greenly, K.C.M.G., C.B.E., M.A.
Léon Greiner.
James Spencer Hollings, C.B.E.
John E. James.
Sir William Larke, K.B.E.
Cyril E. Lloyd.
Aloyse Meyer.
Thomas Turner, M.Sc.
Sir Arthur B. Winder.

Members of Council.

John Harold Andrew, D.Sc.
William Beck Baxter.
Herbert Henry Burton.
Donald Fraser Campbell.
William Frederick Cartwright.
Ian Frederick Lettsom Elliot.
Richard Alan Hacking, M.Sc.
John Watson Jenkin, Ph.D., B.Sc. (Hons.).
J. Sinclair Kerr.
Edward Fulton Law.
Sir Arthur Matthews, O.B.E.
Neville H. Rollason.
Gerald Steel.
Charles Reginald Wheeler, C.B.E.

Hon. Members of Council.

Commercial and Technical Director, British Iron and Steel Federation, Sir John Duncanson.
Director, British Iron and Steel Research Association, Sir Charles F. Goodeve, O.B.E., D.Sc., F.R.S.
President of the Cleveland Institution of Engineers, Chris Moody.
President of The Institute of Metals, Col. P. G. J. Gueterbock, C.B., D.S.O., M.C., M.A.
President of the Lincolnshire Iron and Steel Institute, Wing Commander J. B. R. Brooke, A.M.I.C.E.
President of the Newport and District Metallurgical Society, G. H. Latham.
President of the Sheffield Metallurgical Association, T. F. Russell.
President of the Sheffield Society of Engineers and Metallurgists, Ambrose Firth.
President of the Staffordshire Iron and Steel Institute, G. B. Morrison.
President of the Swansea and District Metallurgical Society, G. J. Jones.
President of the West of Scotland Iron and Steel Institute, J. W. Donaldson, D.Sc. (*Deceased.*)
Representatives of the Institution of Metallurgists, J. E. Hurst, D.Met., W. W. Stevenson.

Secretary: K. Headlam-Morley.

Assistant Secretary: A. E. Chattin, B.Sc. (Hons. Met.), A.R.I.C., F.I.M.

Librarian: R. Elsdon.

Offices.—4, Grosvenor Gardens, London, S.W. 1.

Telegraphic Address.—" Irosamente, Sowest, London."

Telephone.—SLOane 0061.

PREFACE.

The present volume contains twelve papers, seven of which were issued under the auspices of the Joint Research Committees of the Institute and the British Iron and Steel Research Association, which were presented at the Annual General Meeting of the Institute held in London on 1st and 2nd May, 1946, and also the discussion and correspondence on them. Correspondence on five papers (two of them Joint Committee papers) which were presented at this Meeting, but printed in the No. II. volume of the *Journal* for 1945 as they had been set in the smaller format, is also included. In addition, further correspondence and the authors' reply on a paper included in the No. II. volume for 1945, the correspondence on five papers (two of them Joint Committee papers) presented at this Meeting, but published in the preceding *Journal* (having been set in the smaller format), a publication notice of Special Report No. 31, "The Effects of Different Methods of Pretreating Iron and Steel before Painting," by F. Fancutt, and the text of the First Hatfield Memorial Lecture are also included in this book.

Section I. of this volume contains the above material together with the Minutes of the Proceedings of the Meeting, the Report of Council and Statement of Accounts for 1944, and the Presidential Address.

Section II. is devoted to a survey of the literature of the manufacture and properties of iron and steel, and kindred subjects, and consists of a collection of abstracts of articles from the Transactions and Proceedings of scientific societies and from the technical press. This Section also contains reviews of recent books and bibliographies of literature dealing with the manufacture and properties of iron and steel. The matter included in this Section has already appeared in the *Bulletin of The Iron and Steel Institute*, which is issued monthly.

In front of the title-page are inserted lists of Bibliographies and Special Reports issued by the Institute, together with a list of Transactions made available between 1st July, 1946, and 31st December, 1946.

4, Grosvenor Gardens
London, S.W. 1.
12th March, 1947.

CONTENTS.

LIST OF PLATES.

ABBREVIATIONS AND SYMBOLS.

Å.	Ångstrom unit(s) = 1×10^{-10} m.
A.C.	air-cooled; alternating current.
A.H.	air-hardened.
amp.	ampere(s).
amp.hr.	ampere-hour(s).
approx.	approximately.
at.-%	atomic per cent.
at.wt.	atomic weight.
atm.	atmosphere(s) (pressure).
A.W.G.	American wire-guage.
Bé.	Baumé (scale).
b.h.p.	brake horse-power.
B. & S.	Brown and Sharpe (gauge).
B.o.T.	Board of Trade.
b.p.	boiling point.
B.T.U.	Board of Trade unit(s).
B.Th.U.	British thermal unit(s).
B.W.G.	Birmingham wire-gauge.
C.	centigrade (scale).
cal.	calory (-ies).
c.c.	cubic centimetre(s).
c.d.	current density.
c.g.s.	centimetre-gramme-second unit(s).
cm.	centimetre(s).
coeff.	coefficient(s).
conc.	concentrated.
const.	constant(s).
cu.	cubic.
cwt.	hundredweight(s).
D.C.	direct current.
dia.	diameter.
dil.	dilute.
dm.	decimetre(s).
e.m.f.	electromotive force.
e.v.	electron volt(s).
F.	Fahrenheit (scale).
ft.	foot, feet.
ft.lb.	foot-pound(s).
g.	gramme(s).
gal.	gallon(s).
H.F.	high-frequency.
h.p.	horse-power.
h.p.hr.	horse-power-hour(s).
hr.	hour(s).
in.	inch(es).
in.lb.	inch-pound(s).
I.S.W.G.	Imperial standard wire-gauge.
K.	absolute temperature (Kelvin scale).
kg.	kilogramme(s).
kg.cal.	kilogramme-calory(-ies).
kg.m.	kilogramme-metre(s).
km.	kilometre(s).
kV.	kilovolt(s).
kVA.	kilovolt-ampere(s).
kW.	kilowatt(s).
kWh.	kilowatt-hour(s).
kX.	crystal Ångstrom(s) = 1000 Siegbahn X-units.
lb.	pound(s).
L.F.	low-frequency.
M	molar (solution).
m.	metre(s).
m.amp.	milliampere(s).
max.	maximum.
mg.	milligramme(s).
min.	minimum; minute(s).
ml.	millilitre(s).
mm.	millimetre(s).
m.m.f.	magnetomotive force.
m.p.	melting point.
mV	millivolt(s).
mμ	millimicron = 1×10^{-9} m. = 10 Å.
N.	normal (solution).
N.T.P.	normal temperature and pressure.
O.H.	open-hearth; oil-hardened.
O.Q.	oil-quenched.
oz.	ounce(s).
p.d.	potential difference.
*p*H	hydrogen-ion concentration.
p.p.m.	parts per million.
r.p.m.	revolutions per minute.
sec.	second(s).
sp.gr.	specific gravity.
sq.	square.
S.W.G.	standard wire-gauge.
T.	tempered.
temp.	temperature
V.	volt(s).
VA.	volt-ampere(s).
W.	watt(s).
Wh.	watt-hour(s).
W.G.	water-gauge.
W.Q.	water-quenched.
wt.	weight.
wt.-%	weight per cent.
yd.	yard(s).
γ	microgramme(s) = 1×10^{-6} g
μ	micron(s) = 1×10^{-6} m.
$\mu\mu$	1 millionth micron = 1×10^{-12} m. = 0·01 Å.
Ω	ohm(s).
$^\circ$	degree (arc or temperature).
$'$	minute of arc; foot (feet).
$''$	second of arc; inch(es).
$<$	less than.
$>$	greater than.
$\nless$	not less than.
$\ngtr$	not greater than.
$\leqq$	equal to or less than.
$\geqq$	equal to or greater than.
$\neq$	not equal to.
$\equiv$	identically equal to.
$\cong$	approximately equal to.
$\propto$	proportional to.

SECTION I.

MINUTES OF PROCEEDINGS AND PAPERS OF THE IRON AND STEEL INSTITUTE.

ANNUAL GENERAL MEETING

1946

MINUTES OF PROCEEDINGS

AND

PAPERS AND DISCUSSIONS

AT THE

ANNUAL GENERAL MEETING, 1946.

The Seventy-Seventh Annual General Meeting of The Iron and Steel Institute was held at the Offices of the Institute, 4 Grosvenor Gardens, London, S.W.1, on Wednesday and Thursday, 1st and 2nd May, 1946. The sessions on the Wednesday started at 9.45 A.M. and at 2.30 P.M. and that on the Thursday at 9.0 A.M. Mr. Arthur Dorman, Retiring President, was in the Chair during the first part of the proceedings, his place being afterwards taken by Dr. C. H. Desch, F.R.S., the new President.

The minutes of the previous Meeting were taken as read and signed.

Obituary.

The President (Mr. Arthur Dorman): I have to report the death of a Past President of the Institute, Sir Francis Samuelson, Bt., who was President in 1922–24. He was an old friend and colleague of mine on the Board of Messrs. Dorman, Long & Co., Ltd., and he did sterling work for the industry. He had reached a comparatively advanced age.

Dr. Vladislav Sykora, an Honorary Vice-President, died in November, 1945. I have also to record the death of another old friend, Harold E. Wright, the Bessemer Medallist of last year, who died suddenly from a heart attack.

Welcome to Members Attending the Meeting.

The President (Mr. Arthur Dorman): It is pleasant to see such a good attendance at this meeting; it is a good augury for the future. I offer a cordial welcome to you all. A number of foreign and oversea members are now able to be with us, and I welcome them most heartily. I cannot mention them all by name, but you will forgive me if I refer to the presence of His Excellency the Minister for Luxemburg, Dr. Andrew Clasen, whom we made an Honorary Member last autumn, and Dr. George B. Waterhouse, who is this evening going to give us the first of the Hatfield Memorial Lectures. We also have with us Mr. Howard Biers, from Canada, who comes to our meetings so often that we almost think he is a native. We have a number of visitors from the Broken Hill Proprietary Company of Australia. Señor Ramon Quijano and other Spanish friends have come to see us, and we have with us also an old friend, Dr. Durrer, from Switzerland, whom we have not seen for a long time. We have with us a few French, Belgian, and Dutch friends, including M. Bastien from France and M. Zimmer from Belgium. We hope that many more will be able to come next year from these countries. Lastly, we have a strong delegation from Sweden, where the Jernkontoret is going to celebrate next year the 200th anniversary of its foundation.

Presentation of Report of Council and Statement of Accounts for 1945.

The President (Mr. Arthur Dorman), in presenting the Report of Council for 1945, said: There has been an increase of 10% in the number of members of the Institute which at the end of last year was 3,356. After to-day's election we shall have about 3,700 members. This is a far larger figure than we ever contemplated before the war, and is good evidence that the Institute is doing work which is needed.

I think that this meeting is happy evidence that the war is over, even if many difficulties are still before us—and in the steel trade I do not think we can forget that fact to-day! The presence of so many visitors from overseas shows that some of the war-time restrictions have been relaxed.

The chief event during the year has been the arrangements which have been made for affiliation with local societies and for collaboration with the British Iron and Steel Research Association. I attach great importance to the local societies. We have with us to-day Mr. Patchett, of the Cleveland Institution of Engineers, in which I naturally take a great interest. In that body, by reducing our subscription from £2 2*s*. to 15*s*., we quadrupled our membership in a few months. Affiliation with the Institute does help these local societies.

With regard to research, excellent arrangements

have been made for collaboration with the British Iron and Steel Research Association. They are going to take over the Joint Research Committees, and we are going to organize library and information departments for both bodies; and we shall print and publish their reports and papers. I hope that we shall be able to do many things jointly, such as arranging special meetings for sections of the industry, and so on. I think that we can help them also in their foreign relations.

In accordance with these arrangements, the Steel Castings Research Committee was dissolved at the end of the year, and the work taken over by new Committees operating under the Research Association. I am sorry that Mr. W. J. Dawson, who has done such good work as Chairman of the Steel Castings Research Committee, cannot be with us to-day, and we hope that he will soon be fully restored to health. The Committee on the Heterogeneity of Steel Ingots is to continue, but it is transferred to the Research Association as from to-day. The Alloy Steels Research Committee and the Corrosion Committee will be transferred later. These Joint Research Committees have a grand record of work behind them. It is more than 21 years since Dr. Hatfield formed the Committee on the Heterogeneity of Steel Ingots, which has held exactly 150 meetings. I am sure that we are all proud of their work and grateful to the members who have done it. We hope that equally good and perhaps better work will be done in the future.

This seems an appropriate time to congratulate Sir Charles Goodeve, O.B.E., F.R.S., the Director of Research, on his knighthood. We are very pleased that he and Sir John Duncanson have joined our Council, and I am sure that we can help each other.

On the subject of education, I need only refer very briefly to the work of the Joint Committee on Metallurgical Education and to the National Certificates in Metallurgy, which are still in their infancy, but doing well. The new Institution of Metallurgists has received so many applications for membership—well over a thousand in a few months—that I am told that the staff and the Council cannot keep pace with them; the Institute of Metals and our own Institute are providing secretarial assistance. I am sure that it is right that we should encourage this Institution, so that we can all continue to work closely together.

Most of you will already have read in the Press of the generous offer which Dr. Griffiths and The Mond Nickel Co., Ltd., made a few weeks ago, to present £50,000 for Fellowships in Metallurgy. We and the other institutions to whom the offer was made jointly have accepted it with gratitude and enthusiasm. I am glad to see Dr. Griffiths here this morning, so that I can thank him on behalf of us all. I think that this is a very good proposal, and will do a great deal in helping and encouraging young men of ability to become metallurgists. An announcement about the awards will be made as soon as arrangements have been completed, and we hope that this will be in time to make it possible for the first Fellowships to be given this summer.

With regard to publications, the Council have been giving a great deal of attention to the future. As soon as possible we want to bring out the monthly *Journal*, which had to be postponed on the outbreak of war. As a first step, the size of the paper has been increased. We have other plans which I hope will result in our providing a service which will help the local societies and all those in our industry.

I shall ask Mr. Lyttelton, the Honorary Treasurer, to present the Accounts, but before doing so I would mention that we have with us Mr. Pye-Smith, who attended his first meeting of the Institute fifty years ago, and whom we are glad to see looking so well. (*Applause.*)

Mr. A. S. Pye-Smith: I did not become a member of the Institute until 1900, but I accompanied my father in 1896 to the meeting in Bilbao, of which I have very happy recollections.

The Hon. R. G. Lyttelton (Honorary Treasurer) presented the Statement of Accounts for 1945 (*see* pp. 28 P–31 P) and in doing so said: I should like to draw attention to some of the figures, because they occasionally give rise to some anxiety, and we all ought to take a share in that. In the Income and Expenditure Account it will be noticed that the ordinary income increased by £1,500, whilst the expenditure increased by a slightly greater amount, £1,573. The chief item in the increase of £1,500 in the income comes from the increase in members' subscriptions, £675. The item Sales of Publications has increased by £642. The increase in expenditure of £1,573 is largely accounted for by the increasing cost of publications. Publishing and printing give us a good deal of anxiety, both on account of their cost and on account of the delay in getting the printing done. It is nobody's fault on the printing side, and we are usually able to present to you a printed Report of Council. The cost of publications increased by £1,276.

The new activities referred to by the President have cost the rather modest additional sum of £500. The Institute assisted in launching the National Certificates; the increased affiliation with local societies cost £82, and there was a grant of £250 towards the initial expenses of the Institution of Metallurgists. We hope that that body will become self-supporting; it is very anxious to do so.

It will be noticed that salaries, curiously enough,

have been reduced by £1,056. This is partly due to the reorganization resulting from the closer collaboration with the Institute of Metals, but mainly to the shortage of suitable staff. Additional staff is urgently needed. We are very short of typing and other staff. If members find they are not getting prompt answers to their letters, while we should like to know of any real complaints that exist, we hope they will realize that it is due to the very acute shortage of staff and to the increasing membership, which makes it somewhat difficult for the staff to keep abreast of their work. The total salaries will be substantially greater when the Institute is operating on a full peace-time basis. We have made some new appointments since the end of the year, and others will be made as soon as suitable men and women can be found. In that connection, I should like to pay a tribute to the staff for carrying on amid so many difficulties. We are very much beholden to them; they work early and late. (*Applause.*)

The net balance carried forward is slightly reduced, at £415. This is arrived at after taking into account the special subscriptions from companies, for which we are very grateful indeed. As Treasurer, I appreciate that £4,672 is a very substantial help to receive from the steel companies who kindly contribute. Those special subscriptions will come to an end shortly, and it is not intended to ask for them to be renewed; we shall try to get on without them. They have been extremely useful to us, and have enabled us to place to Reserve and Suspense Accounts £1,908, which is quite a substantial figure.

That brings me to the Balance Sheet, which shows that the Reserve and Suspense Accounts now total £14,657, a substantial reserve. The policy of the Council during the war has been to put aside such money as could not be usefully spent, and this conservative policy should make it possible for increased service to be given to members when restrictions are removed and staff becomes available.

Finally, there are the trust funds. The financial position of the trust funds is very good. During the war, a substantial sum has been placed to reserve. The Council hope that as conditions become more normal there will be increased opportunities of spending the income usefully, thus fulfilling the purpose for which the funds exist. Two Williams Prizes were presented in the last financial year, because none was presented the year before. No new Carnegie Scholarship has been given up to date, but the Carnegie Fund is always before the Council, and we try to expend it usefully.

The PRESIDENT moved the adoption of the Report of Council and Statement of Accounts for 1945, and that the thanks of the meeting be accorded to the Honorary Treasurer for his care of the finances of the Institution. The motion was carried unanimously.

AWARD OF THE BESSEMER GOLD MEDAL FOR 1946 TO MR. J. S. HOLLINGS, C.B.E.

The PRESIDENT (Mr. Arthur Dorman): I now have the pleasant duty of presenting the Bessemer Gold Medal for 1946 to Mr. J. S. Hollings, C.B.E. (*Applause.*) He has been all his life in the iron and steel industry. We first met in 1905 at Brymbo. Dorman Long had recently built their Port Clarence steelworks and were anxious for information on active mixers, and so three or four of us went to Chester, and then to Brymbo, where we met Sir Henry B. Robertson, Chairman, and Mr. J. H. Darby, Managing Director of the Company. Mr. Hollings was fortunate in having in his younger days contact with such a great pioneer as Mr. Darby. The works at Brymbo were small, but Mr. Darby made many extraordinarily good innovations, and certainly that visit taught us a great deal and gave us some information that we badly wanted.

Then Mr. Hollings became interested in coke ovens and by-product plants—this was in their earlier days—and supervised the erection of plants in various parts of the country. He later became Managing Director of Brymbo, and when they were taken over by Baldwins he joined the Board of that Company and took a great interest in the management of their Port Talbot works. He built the Cardiff works of Guest Keen Baldwins, which are amongst the finest in the country, and were completed in 1936. There is no doubt that they owe a great deal to Mr. Hollings; the layout was arranged largely on his advice.

Mr. Hollings is a member of the Board of Messrs. Guest Keen Baldwins Iron and Steel Co., Ltd., and its subsidiary companies. He is Chairman of the Pig Iron Conference under the British Iron and Steel Federation, and a member of the Council of that body. He is a member of the Council of the British Iron and Steel Research Association, and a Vice-President of The Iron and Steel Institute. He did a war-time job by helping to black out our works for us, which was a very difficult piece of work. The most miserable time I have ever had was on the few occasions when I wandered about our blacked-out works at night, and we have to thank Mr. Hollings for that! To show their appreciation, the Ministry of Home Security gave him the C.B.E., which was without doubt richly deserved. Mr. Hollings was also one of the consulting engineers on the building of the South African Iron and Steel Corporation works in Pretoria.

We shall all agree, therefore, that Mr. Hollings has well deserved the highest honour which this

Institute can bestow, the Bessemer Gold Medal. (*Applause.*)

The President, amid applause, then made the presentation.

Mr. J. S. Hollings (*in reply*) said : The President has already said so much in such a kind way about me that I feel there is no need for me to say anything, but I should like to assure the Council and all the Members that I highly appreciate receiving this great honour—for it is a great honour—at what is rapidly nearing, at any rate, the close of my career.

I should like to take a few minutes in referring to one or two points which may be of interest. The President was not quite correct in saying that I started life in the iron and steel trade. I started my life down the pit, and served for a sufficient time down the pit to qualify for colliery management. When, however, Mr. John Darby gave me the chance of going abroad and learning what I could about the coke-oven trade, I accepted, and in 1893 I went to Belgium, where I was fortunate enough in a period of three months to see three different coke-oven plants started up. As a matter of fact, I more or less started the third myself, because the manager was courting and preferred to spend his time elsewhere ! It was an invaluable experience for me.

Unfortunately, my then chief, John Darby, had a severe illness which laid him aside for two years, so that I was very much on my own. Young men to-day can hardly conceive the position. I had only one other man on the job who knew anything about it. We were the first to have by-product ovens attached to an iron and steel works in this country, and for the first fortnight I did not take my clothes off ; I slept on the floor of the engine house.

By-product coke, as some of you will know and others may have read (it is a long time ago now), was not at all well received by blast-furnace people in the early days, and, having seen some of the coke that was made, I am not surprised ; but we had to do the best we could with what we had. We had a very high-volatile coal, and, unfortunately for me, alongside the by-product plant were a considerable number of beehive ovens, and the manager of the beehive-oven plant never ceased jibing at me for the coke we were making.

We carried out a number of experiments in blending coal, and definitely established that, by mixing up to 10%, and not more, of anthracite with the high-volatile coal, we improved our coke to the extent that the coke consumption of the blast-furnace was reduced by about 10%. However, as we were able to buy small coal at 2*s*. 6*d*. per ton at the pit, and had to carry the anthracite from South Wales at 12*s*. 6*d*., we had to look about for other ways of doing it. Eventually, about 1899, we went in for compressing the charge before putting it into the oven. That proved an entire success ; it gave us a coke consumption of $1\frac{1}{2}$ cwt. less per ton of pig iron, and made a really good coke.

As far as the coke-oven plant was concerned, the only original experiment which we tried was the recovery of cyanide. We ran it for about two years, but it did not prove a success and had to be given up.

Following that, my next experience, as the President has said, was in going about the country starting up various by-product plants. I returned to Brymbo about 1901 to take charge of blast-furnaces. There I can claim without hesitation to have been the first person to introduce the oxy-coal-gas jet for furnace purposes. We happened to be, as a good many furnaces are occasionally, in a most fearful mess, with five out of our six tuyeres closed up, and it was quite impossible to open the tap-hole. There must be very few men here who remember the days when the only way to open a tap-hole was with a chisel and bar and a hammer. I got into touch with the patentee in Germany ; within 48 hr. he came over, and in less than $\frac{1}{2}$ hr. had opened all the five tuyeres, with less than half a cylinder of oxygen. I have often thought that no invention has taken a greater load off the blast-furnace operator's mind than that, for now he can use the oxygen jet to get out of trouble.

About the same time, I first used what was called " black jack." In 1908 we lined a new blast-furnace which we had built with a complete carbon lining of the hearth, and obtained very good results. The lining came in block form from Germany, but it was very expensive, and when relining the furnace we used the ordinary fireclay brick. In 1910 we put in a dry-blast plant and operated that until the 1914–18 war came, when the Ministry which corresponded to the present Ministry of Supply said " We want your refrigerator coils for a much more important job " and took them away, and they were never restored.

I have been extraordinarily fortunate throughout my career, first of all, in the men under whom I have served and, secondly, in the staff I have had under me. I started under John Darby, a man of enormous energy who early in his career became unable to get about the country, and who used to send me. I think that between 1895 and 1912 there was hardly a year when I did not go abroad to visit one works or another, and sometimes I went two or three times a year. I worked with Darby until he left Brymbo in 1908. Ten years after that, as the President has said, I joined Baldwins, and for a time served under Sir John Roper Wright, who was also a pioneer. With the late Sir William Siemens, he introduced the re-

generative furnace into this country and made the first acid open-hearth steel. Sir John at that time was advanced in years, and on his death I came under my present chief, who is known to you all and throughout the trade all over the world. I have always received the same encouragement and friendly treatment from Sir Charles Wright as I had from my earlier chiefs. I hope that the young men here may be as fortunate in that respect as I have been.

One thing more. We meet here as a technical Institute, and perhaps may be inclined to attach, and quite rightly, great importance to technical achievements; but, looking to the future, I fancy that one of the most important ways in which we can improve our practice and our output is by getting closer to our men. (*Applause.*)

The PRESIDENT (Mr. Arthur Dorman): Mr. Hollings has given a great deal of credit to others, but I feel that his own personality and ability have had much to do with his success. (*Applause.*)

PRESENTATION OF WILLIAMS PRIZES.

The PRESIDENT (Mr. Arthur Dorman): This year two Williams Prizes have been awarded, one to Dr. R. Jackson, of Messrs. Hadfields, Ltd., for his paper on "The Application of Radiography to the Improvement of Foundry Technique"; and the other to Mr. T. F. Pearson, of Messrs. Colvilles, Ltd., for his paper on "The Improvement of the Citric-Acid Solubility of Basic Open-Hearth Slags containing Fluorspar." (*See Journal of The Iron and Steel Institute*, 1945, No. I., pp. 225 P–259 P, and 1945, No. II., pp. 441 P–453 P, respectively.)

The President then, amid applause, presented the two Williams Prizes.

FORMATION OF AN IRON AND STEEL ENGINEERING GROUP.

The SECRETARY (Mr. K. Headlam-Morley): Arising out of a meeting of the Council held in March, it has been decided to set up an Iron and Steel Engineering Group of members of The Iron and Steel Institute to carry out the activities and functions of the Institute for engineers engaged in the iron and steel industry and in the design and manufacture of plant for the industry. As head of the Group, an Engineering Committee has been set up under the Council. It will organize discussions and conferences, both centrally and locally, on subjects of interest to members of the Group. Affiliated local societies will be asked to collaborate. The Committee will also encourage the publication of papers on such subjects and take such other action as is necessary to meet the objects of the Group.

A circular will be issued on the subject. Members of the Institute who wish to become members of this Group should return the circular to me. Others interested should join the Institute in the ordinary way, indicating their desire to join this Group also on their application form. There is no additional membership fee.

CHANGES ON THE COUNCIL.

The SECRETARY (Mr. K. Headlam-Morley): I have to report the following changes on the Council since the last General Meeting in the autumn:

New Honorary Vice-Presidents.—Mr. Fred Clements, Mr. E. J. Fox, and Sir William Larke, K.B.E.

New Vice-Presidents.—Mr. W. J. Dawson and Mr. G. H. Latham.

New Members of Council.—Sir Arthur Matthews, Mr. C. R. Wheeler, Mr. D. F. Campbell, and Dr. J. W. Jenkin.

New Honorary Members of Council.—Sir Charles Goodeve, O.B.E., F.R.S. and Sir John Duncanson.

In addition, the following Presidents of other societies have become Honorary Members of Council during their periods of office: Colonel P. G. J. Gueterbock, succeeding Dr. W. T. Griffiths (Institute of Metals); Mr. J. H. Patchett, following Mr. L. Wright (Cleveland Institution of Engineers); Mr. H. Bull, succeeding Mr. A. A. Munro (Sheffield Metallurgical Association); Mr. Ambrose Firth, succeeding Mr. F. Wardrobe (Sheffield Society of Engineers and Metallurgists); and Wing Commander J. B. R. Brooke, succeeding Mr. C. A. J. Behrendt (Lincolnshire Iron and Steel Institute).

Principal Edwards, who had been nominated an Honorary Vice-President, has resigned his membership of the Council as he is unable to attend the meetings. The Council have accepted his resignation with regret.

In accordance with Bye-Law No. 10, the names of the following Vice-Presidents and Members of Council were announced at the last Autumn Meeting as being due to retire at the present Annual Meeting. As Sir William Larke, K.B.E., has become an Honorary Vice-President, and Mr. W. J. Dawson has been elected a Vice-President, Dr. A. McCance, F.R.S., and Mr. E. F. Law become due to retire in their place:

Vice-Presidents.—Mr. J. R. Menzies-Wilson, Mr. C. E. Lloyd, and Sir William Larke, K.B.E.

Members of Council.—Professor J. H. Andrew, Mr. W. B. Baxter, Mr. W. J. Dawson, Mr. Gerald Steel, and Mr. I. F. L. Elliot.

No other members having been nominated up to

one month previous to the present meeting, the retiring Vice-Presidents and Members of Council are presented for re-election.

The Iron and Steel Institute Foundry Prize.

The Secretary (Mr. K. Headlam-Morley): The Iron and Steel Institute Foundry Prize, awarded to the candidate in the degree examinations at Sheffield University who obtains the highest number of marks, was this year awarded to Mr. P. W. Hyde.

Ballot for the Election of Members and Associates.

Mr. J. H. Patchett (Middlesborough) and Mr. J. T. Wright (Stourbridge) who were appointed scrutineers of the ballot, reported that the following two hundred and ninety-six candidates for membership and ninety-three for associateship had been duly elected:

Members.

Aal, Willem, Amsterdam, Holland.
Adams, Joseph Harry, Mostyn, Flintshire.
Ageew, *Professor* Nicholas W., D.Sc., Met.Eng., Moscow, U.S.S.R.
Aksu, Aziz, Karabuk, Turkey.
Alexander, George Frederick, Transvaal, South Africa.
Allen, Kenneth Alfred, M.Sc. (N.Z.), A.R.I.C., A.A.C.I., Melbourne, Australia.
Almunia y de León, Joaquin, Bilbao, Spain.
Anderson, Alexander Laird, Cambuslang, Scotland.
Årmann, Bror Nils Jacob, Björneborg, Sweden.
Astley, William, Weybridge, Surrey.
Atha, Andrew, London.
Auld, James, Paisley.
Austin, Victor, Swansea.
Badger, Arthur, Rotherham.
Bagnall, Frank Taylor, Stocksbridge, Sheffield.
Baxter, Alan Hoole, Sheffield.
Bayindir, *Dipl. Ing.*, Ismail, Karabuk, Turkey.
Baylas, Vahdet, Karabuk, Turkey.
Bayramoglu, Kenan, Karabuk, Turkey.
Beese, John James, Ebbw Vale, Mon.
Beighton, Alfred, Sheffield.
Bell, David, Corby, Northants.
Bell, Douglas James, Corby, Northants.
Bell, Harold, Consett, Co. Durham.
Beresford, W. L., Stanton, Nottingham.
Bibby, Eric Winters, Stocksbridge.
Bishop, Alfonso Obispo, Asturias, Spain.
Blackbourn, J. I., Stanton, Nottingham.
Blackledge, Bertram Ewart, M.I.Chem.E., Port Talbot, Glam.
Blair, James Stone, Ebbw Vale, Mon.
Bligh, Arthur Robert, M.A., Singapore.
Boël, Pol Gustave, La Louvière, Belgium.
Bouchet, Jean, Paris, France.
Bowen, N. B., Stanton, Nottingham.
Brachet, Claude, Paris, France.
Bradwell, L., Stanton, Nottingham.
Bramhall, E., Stanton, Nottingham.
Brandsma, *Professor Dr. Tr.*, Delft, Holland.
Brouillet, Ignace, B.Sc., Montreal, Canada.
Brown, John Willis, B.A., M.I.Mech.E., Shifnal, Shropshire.
Brun, Max, Rombas, Moselle, France.
Bruton, Albert Leslie, London.
Bryant, Jack Ronald, B.Sc.(Eng.), Bedford.
Burton, Harry Wade, London.
Butler, John Henley, Consett, Co. Durham.
Cairns, James, Cambuslang, Scotland.
Camdibi, Ferhan, Karabuk, Turkey.
Capmany Arbat, Joseph, Mieres, Spain.
Ceairns, C., Stanton, Nottingham.
Chadeyron, A. A. G., B.Sc.(Lond.), A.R.I.C., Middlesborough.
Child, Vernon Walter, Ipswich.
Chomelle, Pierre, Paris, France.
Clasen, Leo A., London.
Claydon, Sydney Edward, Birmingham.
Cleminson, George, Bulawayo, Africa.
Clift, Alfred, Bilston, Staffs.
Cook, Albert Edward, Darnall, Sheffield.
Cooke, Roger Gresham, M.A., Sheffield.
Corke, Joseph, Middlesborough.
Cornforth, Stephen, Middlesborough.
Cornubert, *Professor* Raymond, Nancy, France.
Coudel, Jean, Réhon, France.
Cox, Oliver, Bilston, Staffs.
Crancée, Georges, Valenciennes, France.
Craven, Stanley William, Northwich, Cheshire.
Crellin, George, Corby, Northants.
Croft, John Edward, Consett, Co. Durham.
Cuthbertson, Joseph William, B.Sc., M.Sc., D.Sc., Greenford, Mdx.
Cuthill, Alexander Scott, Sheffield.
Daniel, John Leslie, Corby, Northants.
Dardenne, Roger L., Louvroil, France.
Davies, Emrys, Landore, Glam.
Davies, Henry Hugh Joynson, Irlam, Manchester.
Davies, Ivor, Ebbw Vale, Mon.
Davies, John Talfryn, Port Talbot, Glam.
Denham, James, Middlesborough.
Denizman, Turgut, Karabuk, Turkey.
Dias da Fonseca e Almeida, Eduardo Hubert, Lisbon, Portugal.
Dobbins, Norman Edwin, Ph.D., M.Sc., B.Sc.(Lond.), Transvaal, South Africa.
Doganay, Cemal, Karabuk, Turkey.
Doherty, Frederick Campbell, Corby, Northants.
Drane, Henry Donald Hector, Ph.D., M.Sc., A.M.I.E.E., A.M.I.Chem.E., London.
Dunlop, John D., Bilston, Staffs.
Dutton, A., Irlam, Manchester.
Eckersley, Fredric, Belfast, N.I.
Ellwood, Edwin Cyril, B.Sc.(Eng.), Newcastle-on-Tyne.
Erskine, John, B.Sc., Burnside, Lanark.
Etker, *Dipl. Ing.* Sedat, Karabuk, Turkey.
Femir, *Dipl. Ing.*, Mehmet, Karabuk, Turkey.
Fenby, Colin Ronald, Edinburgh.
Fiennes, Maurice Alberic, Sheffield.
Finch, Stephen Lonsdale, Letchworth, Herts.
Finn, Joseph, Newcastle, N.S.W., Australia.
Freeman, Henry Alfred, Corby, Northants.
Freeman, Reginald Ernest, B.Sc., Mostyn, Flintshire.
Frith, John Grooby, Sheffield.
Gevers, Michel, A.I.Ig., Grivegnée, Belgium.
Glen, James, Corby, Northants.
Glen, John, Corby, Northants.
Glen, John, Market Harborough, Leics.
Godenne, Jean, Anzin, France.
Gökyigit, Necati, M.Sc., Karabuk, Turkey.
Gonenc, Remziye, Karabuk, Turkey.
Goodfellow, Stanley, London.
Goodlad, Wilfred Horace, Sheffield.
Gorman, Leonard, Corby, Northants.
Gossedge, William Oswald, Ebbw Vale, Mon.
Graaf, *Ir.* Y. E. de, Ymuiden, Holland.

GRANT, THOMAS MORE, F.C.I.S., F.I.C.A., Newcastle-on-Tyne.
GREGORY, DONALD, Ebbw Vale, Mon.
GRUNIAUX, MARCEL EMILE, Longwy-Bas, France.
GUNDAY, FARUK, Karabuk, Turkey.
GUNDERSON, CHARLES TERENCE, Newcastle, N.S.W., Australia.
HABERSHON, JOHN WINTER, M.A., Rotherham.
HABERSHON, RICHARD PERCY RIX, Rotherham.
HADDEN, WILLIAM M., Giffnock, Renfrew.
HALDAR, MANMATHA KUMAR, M.Sc., B.Met.(Hons.), Sheffield.
HALET, EMILE A., London.
HARRIS, IVOR, East Moors, Cardiff.
HARRIS, LEO, Landore, Glam.
HARRIS, RONALD HERBERT, B.Sc., A.R.S.M., London.
HART, WILLIAM WATSON, Consett, Co. Durham.
HENDERSON, *Miss* ISABEL JEAN, M.Sc., Avonmouth, Bristol.
HEY, JOHN, Consett, Co. Durham.
HIME, MERVYN GEORGE WALTER, Rio de Janeiro, Brazil, S. America.
HIPWELL, CECIL, London.
HIRST, HENRY, Ph.D., B.Sc. (Eng.), Melbourne, Australia.
HIRST, THOMAS BAYLISS VERNEY, Manchester.
HOGARTH, THOMAS A., Llanelly, Carmarthenshire.
HOLIDAY, JOSHUA DUMVILLE, Irlam, Manchester.
HOPKINS, DONALD WALTER, B.Sc., Swansea, Glam.
HORABIN, W., Stanton, Nottingham.
HORNSBY, WILLIAM, A.M.Inst.W., London.
HOWDEN, HUGH, Glasgow.
HULT, JONAS, Boxholm, Sweden.
HYND, JOHN, London.
ILTER, HAZIM, Karabuk, Turkey.
ISFENDIYAROGLU, *Dipl. Ing.*, FATIN, Karabuk, Turkey.
IVENS, KENNETH, Corby, Northants.
IVETT, ALBERT EDWARD, Landore, Glam.
JACKSON, W., Stanton, Nottingham.
JARVIS, EDMUND ERNEST, B.Sc., Singapore.
JOHNSON, WILLIAM ARNOLD, M.A., M.Inst.C.E., M.I.Mech.E., Stocksbridge, Sheffield.
JONES, JOHN RAYMOND, Landore, Glam.
JONES, ROBERT, B.Sc., Bilston, Staffs.
JONES, STANLEY, Bradford.
JONES, THOMAS WALTER, Landore, Glam.
KALLING, SVEN OTTO STURE, Met.(Eng.), Nykroppa, Sweden.
KAPRALI, *Dipl. Ing.* EKREM, Karabuk, Turkey.
KHAN, MAHMUD, M.Sc., Leeds.
KHAN, SITESH CHANDRA, B.Sc., Calcutta, India.
KIRKALDY, WILLIAM JOHN FAWCITT, Leeds.
KJELLBERG, BJÖRN OSCAR, Met.(Eng.), Gothenburg, Sweden.
KNIGHTS, EDWARD DONOVAN, B.Sc., Derby.
KUBELIK, *Dr. Ing.*, TAROSLAV, Ostraire, Czechoslovakia.
KYNASTON, ALAN HERBERT, Corby, Northants.
LAKE, R. A., Irlam, Manchester.
LATOURTE, JEAN, Paris, France.
LAURENT, PIERRE, D.Sc., Paris, France.
LAWRIE, R. D., Stanton, Nottingham.
LECKIE, ALAN HARVEY, Ph.D., B.Sc., F.R.I.C., London.
LEE, ARTHUR WAKEFIELD, B.Sc.(Tech.), A.M.I.Mech.E., Scunthorpe, Lincs.
LEE, GEOFFREY, Bilston, Staffs.
LEE, PHILIP ARTHUR, B.A.(Eng.), Sheffield.
LEFEBVRE, *Professor* ACHILLE GEORGES, Brussels, Belgium.
LEROY, ANDRÉ, Paris, France.
LESSNER, CHARLES, Pontevedra, Spain.
LEWIS, JAMES ESSINGTON, B.Met.Eng., Newcastle, N.S.W., Australia.
LINNEY, JAMES ARTHUR, Griffithstown, Mon.
LOVE, DAVID A., Bearsden, Glasgow.
LOVLEE, JOHN, Corby, Northants.
MCCAIN, LAURENCE HENRY, Sheffield.
MCEWAN, GORDON JOHN, B.Sc., Bilston, Staffs.
MAGSON, LEONARD WILLIAM, B.Sc., A.Inst.P., Glasgow.
MALCOR, HENRI, Paris, France.
MALOTAUX, R. N. M. A., Amsterdam, Holland.
MATTHEWS, STANLEY, Landore, Glam.
MAXWELL, RONALD, Consett, Co. Durham.
MAYNE, JOHN SHEARER, Sheffield.
MAYNE, PHILIP, M.A., Billingham, Co. Durham.
MAZARRASA QUIJANO, JOSÉ A., Santander, Spain.
MEADLEY, ALLAN HOWARD, Corby, Northants.
MENSFORTH, ERIC, C.B.E., M.I.Mech.E., M.I.P.E., F.R.Ae.S., Sheffield.
MERCIER, ANDRÉ, Paris, France.
MEYNADIER, HENRI, Homécourt, France.
MIDDLETON, THOMAS REGINALD, B.Sc., Sheffield.
MISSET, JEAN, Paris, France.
MITCHELL, WILLIAM JAMES JOHN, East Moors, Cardiff.
MONNERET, FLORENT, Le Havre, France.
MONTGOMERY, WILLIAM, Glasgow.
MORLEY, HERBERT, Stocksbridge, Sheffield.
MORRISH, AUBREY HENRY JOHN, Tyseley, Birmingham.
MOTTRAM, HARRY, Sheffield.
MOUSLEY, R. G., Irlam, Manchester.
MUIR, WILLIAM, Corby, Northants.
NASH, CHARLES ARTHUR, Consett, Co. Durham.
NEIL, MAGNUS, Consett, Co. Durham.
NICHOLS, FREDERICK, Corby, Northants.
NORGARD, JOHN DAVEY, B.Eng., Melbourne, Australia.
NORTH, JOSEPH EDWARD, London.
ORS, FIKRET, B.Sc., Karabuk, Turkey.
OTERO NAVASCUÉS, *Commander* JOSE M., Madrid, Spain.
PALM, *Ir.* JAN HENDRIK, Amsterdam, Holland.
PARIS, PIERRE, Neuves-Maisons, France.
PEDDIE, RONALD, Sheffield.
PETERS, JAMES, Bilston, Staffs.
PETIT, DANIEL, Paris, France.
PHILPOT, A. J., C.B.E., M.A., B.Sc., F.Inst.P., London.
PICKLES, CLIFFORD HAMMOND, Corby, Northants.
PIERCE, EARL W., Chicago, Illinois, U.S.A.
PINCHIN, H., Stanton, Nottingham.
PINEDO SALZEDO, OSVALDO, Bogota, Colombia, S. America.
PLUHAŘ, *Eng.* ADOLF, Pilsen, Czechoslovakia.
POWELL, A., Irlam, Manchester.
POWELL, REGINALD DAVID, Newport, Mon.
POWER, THOMAS, East Moors, Cardiff.
PRESCOTT, PETER ROLAND, Birmingham.
PRICE, FRANK, Irlam, Manchester
PURVIS, ROBERT, Consett, Co. Durham.
QUILTER, GEORGE WILLIAM, Croydon, Surrey.
RAMSAY, IVER MARTIN, Newcastle, N.S.W., Australia.
REED, ALBERT WILLIAM, Consett, Co. Durham.
REES, HARRY WYNFORD IVOR, Consett, Co. Durham.
REES, OLIVER EVAN, Swansea, Glam.
REYNAUD, ANDRÉ, Paris, France.
RICHARDS, THOMAS EDWARD, Consett, Co. Durham.
RICHARDS, WINDSOR, Ebbw Vale, Mon.
RILEY, GEOFFREY, Bilston, Staffs.
RIVIERE MANEN, LUIS, Barcelona, Spain.
ROBERTS, DAVID, M.P.S., Mostyn, Flintshire.
ROBINSON, CECIL WHITEOAK, Birmingham.
RODEN, H., Stanton, Nottingham.
ROWE, KENNETH WATSON, Newcastle, N.S.W., Australia.
RUDORFF, DAGOBERT WILLIAM, London.
RUSSELL, DAVID CLARK, Cawnpore, India.
RUSSELL, FRANK, Landore, Glam.
RYAN, HAROLD MARK, Stockton-on-Tees.
SAHLIN, BENGT INGEMAR, Stockholm, Sweden.
SARGENT, BERTIE ARTHUR, London.
SCHENSTRÖM, JOHAN MAGNUS, Surahammar, Sweden.
SCHNEIDER, CHARLES, Paris, France.
SCOTT, NORMAN WILKINSON GLENDINNING, Consett, Co. Durham.

Setterwall, Carl Albin Magnus, Stockholm, Sweden.
Sharp, Kenneth Copley, Middlesborough.
Shaw, Esmond, Irlam, Manchester.
Short, Joseph, B.Sc., Rosyth, Scotland.
Skerl, John George Anthony, D.Sc., London.
Skilton, Henry George, Melbourne, Australia.
Smellie, Gavin, Port Talbot, Glam.
Smith, Jack Bernard, Corby, Northants.
Sønnichsen, Arne, Oslo, Norway.
Spruce, Frederick George, Bilston, Staffs.
Spurgeon, Christopher Edward, C.B.E., M.I.Mech.E., London.
Stanley, William John, Ruddington, Notts.
Starbuck, Leslie, Bilston, Staffs.
Stein, Colin Hunter, Bonnybridge, Scotland.
Stokes, Fred, Irlam, Manchester.
Suff, Daniel W., Swansea, Glam.
Sullivan, Haldane Herbert, Newport, Mon.
Sutherland, Hugh McDonald, Sheffield.
Taylor, A. J., Stanton, Nottingham.
Taylor, Herbert Henry, Irlam, Manchester.
Taylor, John, Ph.D., M.Sc., Glasgow.
Thomas, Ivor, Landore, Glam.
Thorneycroft, James Alex. C., Corby, Northants.
Thurlow, Stanley Maurice, Newcastle, N.S.W., Australia.
Tiner, Nevzat, Ph.D., Karabuk, Turkey.
Toft, John Leslie, Irlam, Manchester.
Tomlinson, Harry Victor, Consett, Co. Durham.
Törneman, Björn Yngue, Surahammar, Sweden.
Tournaire, Marcel, Paris, France.
Treharne, David Myrddin, Ebbw Vale, Mon.
Tschudnowsky, Jean Roger, Paris, France.
Turkan, Meliha, Karabuk, Turkey.
Tyszka, *Dipl. Ing.* Leszek, Karabuk, Turkey.
Ucak, *Dipl. Ing.* Orhan, Karabuk, Turkey.
Veselý, *Ing.* Lubomír, Prague, Czechoslovakia.
Vibart, Hugh Henry Rose, M.A., B.Litt.(Oxon.), London.
Ward, Walter Eric, Consett, Co. Durham.
Weller, Frank, Corby, Northants.
Westwood, William Henry, Bilston, Staffs.
Wijkander, Rutger, Smedjebacken, Sweden.
Williams, Arthur, Landore, Glam.
Williams, Emrys, Landore, Glam.
Williams, Ernest Francis, Landore, Glam.
Williams, Thomas, Ruddington, Notts.
Williamson, H., Stanton, Nottingham.
Wingate, David, Coatbridge, Lanark.
Winter, William Herbert, London.
Wood, George Andrew, Sheffield.
Worne, Sidney, London.
Wotton, James Edwin, Newport, Mon.
Wurth, Jean, Athus, Belgium.
Wynn, William John, Newport, Mon.
Zickrick, Lyall, Schenectady, New York, U.S.A.
Zimmer, František, Brussels, Belgium.

Associates.

Allender, Peter John, Birmingham.
Armstrong, Alec William, Birmingham.
Ashley, Herbert Stanley, Bilston, Staffs.
Ashton, Stanley James, Liverpool.
Barker, John Julian, East Moors, Cardiff.
Bevan, Austin Henry, East Moors, Cardiff.
Biggs, William Derrick, Manchester.
Bishop, William Charles, Landore, Glam.
Blickwede, Donald J., Cambridge, Mass., U.S.A.
Brooks, Stanley Hogarth, Corby, Northants.
Butcher, Roy, Stocksbridge, Sheffield.
Campbell, William John, Lutterworth, Rugby.
Carswell, Arnold Clive, High Wycombe, Bucks.
Carter, Reginald D., Leeds.
Clay, Derek Bryan, Stocksbridge, Sheffield.
Crosta, Terence William, East Moors, Cardiff.
Davies, Llewellyn Lloyd, Neath, Glam.
Davies, William, Bilston, Staffs.
Dearnley, George Stuart, Leeds.
Dixon, Harold Evans, London.
Douglas, Ian Holmes, B.Met., London.
Dudley-Jones, David Trevor, Ebbw Vale, Mon.
Duff, William, B.Sc., Coatbridge, Lanark.
Evans, John, East Moors, Cardiff.
Evans, John Jones, Ebbw Vale, Mon.
Fern, William Marrwood, Glasgow.
Fisher, Thomas Frank, Edgware, Mdx.
Fletcher, William Corcoran, B.Sc., Corby, Northants.
Fowler, Basil Stanley, Ebbw Vale, Mon.
Fowler, Harry, Sheffield.
Freer, William George, Scunthorpe, Lincs.
Gainsbury, Peter Edward, Hayes, Mdx.
Halliwell, James, Redditch, Worcs.
Hancock, John, Woodley, Stockport.
Hansen, Peter John, Swansea, Glam.
Hart, Richard, Coatbridge, Lanark.
Hay, William, Coatbridge, Lanark.
Helliwell, Ralph, Liverpool.
Hilliard, John Evelyn, Liverpool.
Hinde, John Michael, Stocksbridge, Sheffield.
Holloway, John, Bilston, Staffs.
Hulse, Clifford, B.Sc., Sheffield.
Jackson, John Stephen, B.Sc.(Hons.), Warrington, Lancs.
Jackson, K., B.Sc., North Wembley, Mdx.
James, Kenneth William, Ebbw Vale, Mon.
Jamieson, Dick, Glasgow.
Johnson, Howard Frederick, Tyseley, Birmingham.
Jones, Densil, Landore, Glam.
Jones, Frederick Oakley, Swansea.
Jones, Gordon Vincent, Llanelly, Carmarthenshire.
Jones, Thomas Ivor, Port Talbot, Mon.
King, Robert Dick, Scunthorpe, Lincs.
Lagercrantz, Carl Bertil Bengt, Surrahammar, Sweden.
Lane, Derek, Tinsley, Sheffield.
Lucas, Geoffrey, Leeds.
McCulloch, Thomas, Coatbridge, Lanark.
McDowall, Ian Pearson, Corby, Northants.
Mackenzie, Ian Manson, Wishaw, Lanark.
Marshall, Kenneth, Tinsley, Sheffield.
Morgan, Dennis Francis, Griffithstown, Mon.
Morton, Robert Louden, South Renfrew, Scotland.
Naysmith, James, Glasgow.
Newton, Neville Yoxall, B.Sc., Sheffield.
Nickson, Michael Charles, B.Sc., Birmingham.
North, Philip Edward, Wakefield, Yorks.
Parkins, Redvers Nicholson, B.Sc., Durham.
Partridge, John Montague, East Moors, Cardiff.
Pearson, Harold, Bilston, Staffs.
Pillans, Stuart, East Moors, Cardiff.
Postlethwaite, Alan William, B.Met.(Hons.), Stafford.
Purcell, Philip Ralph, Corby, Northants.
Rees, Daniel, Landore, Glam.
Roberts, John Aelwyn, Blaenau Ffestiniog, N. Wales.
Roberts, Joseph Edward, Liverpool.
Robertson, Thomas Macdonald, B.Sc., Glasgow.
Rogers, Stanley Edwin, Swansea.
Saunders, William Bernard John, Griffithstown, Mon.
Simms, Harry, Scunthorpe, Lincs.
Smellie, William James, London.
Smith, William Roy, Farnborough, Hampshire.
Southall, Joseph, Bilston, Staffs.
Stanfield, Colin Campbell McKenzie, Motherwell, Lanark.
Storey, Clifford, Stocksbridge, Sheffield.

TALBOT, DAVID E. J., Swansea.
TOFT, LESLIE HOWARD, B.Sc.(Eng.), Birmingham.
URIE, THOMAS, Glasgow.
WHEELWRIGHT, FRANCIS THOMAS, Kidderminster, Worcs.
WILLIAMS, HAULWYN, B.Sc., Pontardawe, Glam.
WILLIAMS, PETER, East Moors, Cardiff.
WILLIAMS, ROY, Landore, Glam.
WILSON, JOHN GEOFFREY, B.Met., Scunthorpe, Lincs.
WILSON, JOSEPH BEATTIE, Clifton, Manchester.
WINTON, JOHN, Leeds.

INDUCTION OF THE PRESIDENT-ELECT, DR. C. H. DESCH, F.R.S.

Mr. ARTHUR DORMAN (Retiring President): We now come to the induction of the new President, but I should like first of all to thank the Members of Council for the unfailing help which they have given me during my two years of office. I look back on those years with great pleasure and pride, because I feel that it is an honour to be President of an Institute such as this, which is a very live body, and which under Dr. Desch may be still more alive. I should also like to thank the Secretary and the staff for their loyal support during these two years.

Dr. Desch is a great scientist, and a Fellow of the Royal Society. We have known him for many years, and we appreciate the great work which he has done. What strikes me about him is that he is such a quiet, able lecturer; he clearly knows his subject, and is able to present it in a way which makes a tremendous appeal to me.

He takes over the Presidency at a very important time, and I feel that the Institute is very fortunate indeed to have induced him to undertake this office at this time. Our relationship with the British Iron and Steel Research Association, thanks to Sir Charles Goodeve, promises very well, and we could not have a better man than Dr. Desch to improve those relations.

To enumerate all the offices and positions which Dr. Desch has held would almost fill a volume, but he has been Professor of Metallurgy at the Royal Technical College, Glasgow, and at Sheffield University. He has been Technical Adviser to the Iron and Steel Industrial Research Council (the body now replaced by the British Iron and Steel Research Association), and Technical Director of Messrs. Richard Thomas and Baldwins, Ltd., and he is now Technical Adviser to the Whitehead Iron and Steel Co., Ltd. He has written numerous scientific papers, and his textbook on Metallography, now in its sixth edition, is a standard work. He has also, in collaboration with Mr. Lea, written a book * on the chemistry of cement and concrete.

He has been a member of The Iron and Steel Institute since 1913, and was Vice-President in 1930. He was awarded the Bessemer Gold Medal in 1938. There is no greater name in the metallurgical field than that of Dr. Desch, and I hand over the Presidency to him with great pleasure and great confidence, and wish him a happy and successful term of office as President of the Institute. (*Applause.*)

* F. M. Lea and C. H. Desch, "The Chemistry of Cement and Concrete." London, 1935: Edward Arnold and Co.

Mr. ARTHUR DORMAN then left the Chair, which was taken, amid applause, by the incoming President, Dr. C. H. DESCH, F.R.S.

VOTE OF THANKS TO THE RETIRING PRESIDENT.

The PRESIDENT (Dr. C. H. Desch, F.R.S.): On assuming office, my first duty is to move that the very best thanks of the Institute be given to Mr. Arthur Dorman for his services as President during the last two years. I do so with the greatest of pleasure. We have found in Mr. Dorman a most excellent President, always genial and good-tempered and extremely efficient. Those of us who have sat under him on the Council and have been concerned with the business of the Institute have found it a most pleasant collaboration.

Mr. Dorman is a distinguished steel manufacturer from one of the most important steelmaking districts in Europe, and we are delighted that he should have found the time to take on the office of President and to fulfil its duties so completely. He has been very regular in attending the meetings, and has performed his duties with the highest efficiency. (*Applause.*)

Sir WILLIAM LARKE, K.B.E.: It gives me particular pleasure to second the motion, although I am sure it is a work of supererogation. I have known Mr. Dorman fairly intimately almost ever since he came down from Cambridge and entered the great firm of which he is now one of the distinguished leaders. During that period I have formed not only an affectionate regard for him, but an ever-growing respect for his personal development in the art of industrial leadership, as well as his high technical appreciation of the progressive discoveries which have made the industry what it is.

The vote of thanks was carried unanimously, with acclamation.

Mr. ARTHUR DORMAN: I very highly appreciate the vote of thanks which you have accorded me. I look back on the past two years with great pleasure. It has been an interesting time, and what has gratified me most has been the great increase in membership and enthusiasm.

PRESENTATION OF THE PRESIDENTIAL ADDRESS.

The PRESIDENT (Dr. C. H. Desch, F.R.S.) delivered his Presidential Address. The text will be found on pp. 33 P.–40 P.

The Hon. R. G. Lyttelton (Hon. Treasurer): I beg to propose that a hearty vote of thanks be accorded to the President for his important and most interesting Address. It is our practice not to discuss the President's Address, but I am sure you will agree that it will have a most definite influence in bringing the subject of metallurgical education and the services that science can render to the industry to increased public attention. It provides very valuable material for useful discussion outside, and performs a marked and historical service in furthering the essential cause of metallurgical education.

Dr. George B. Waterhouse: I have pleasure in seconding the motion. It is unfortunate that the Address is not subject to discussion, but it is subject to careful reading and study, and will be very helpful to everyone. The problems are the same, as the industries are the same, in different countries.

The vote of thanks was carried unanimously, with acclamation, and was briefly acknowledged by the President.

Votes of Thanks.

To the Authors.

The President (Dr. C. H. Desch, F.R.S.): We have had an excellent discussion. Throughout this meeting we have not had votes of thanks to the separate authors, so I now make the omnibus proposal that the best thanks of the Institute be given to the authors of all the papers and to those who have taken part in these very valuable discussions.

The vote of thanks was carried with acclamation.

To the President.

Sir Charles Goodeve, O.B.E., F.R.S.: I am sure that those present would like to express their appreciation of the remarkable way in which you, Sir, have handled this Meeting.

I am a very new member, and this is the first meeting of the Institute which I have attended, but I have attended many scientific conferences and perhaps I may say I have never attended one which has gone with such a swing as this. I think a great deal of the credit for that should be given to our President. Not only has he handled the usual problems which fall to a President, but he commenced the proceedings with a magnificent and inspiring address which should have repercussions for a long time. He has welded the speakers' remarks together by his own little bits in between and, furthermore, he has made positive scientific contributions to the discussion.

On behalf of those present, I thank you very much, Sir, for your able chairmanship and I look forward to further meetings under your chairmanship.

The vote of thanks was carried with acclamation.

The President: I thank Sir Charles Goodeve for his kind remarks. I am glad we have held such a successful meeting, the first to be held under conditions approaching normal.

The proceedings then terminated.

The First Hatfield Memorial Lecture.

Dr. George B. Waterhouse, Professor Emeritus of the Massachusetts Institute of Technology, presented the First Hatfield Memorial Lecture, on "The Services to Mêtallurgy of the Late Dr. W. H. Hatfield, F.R.S.," on 1st May, 1946, at 8.30 P.M. at The Institution of Civil Engineers, Great George Street, London, S.W. 1. (*See* pp. 369 P–376 P.)

Members' Luncheon.

A Luncheon was held at the Connaught Rooms, Great Queen Street, London, W.C. 2, on Thursday, 2nd May, 1946. Dr. C. H. Desch, F.R.S., President of the Institute, occupied the Chair, and some five hundred members and guests were present. The guests included: The Rt. Hon. John Wilmot, M.P. (Minister of Supply); His Excellency M. Björn Prytz (Swedish Minister); His Excellency Dr. A. J. Clasen (Luxemburg Minister); The Rt. Hon. The Earl of Dudley, M.C.; M. Des Aubrys (Secretary-General of the Mission of the French Ministry of Industrial Production); Lt.-Gen. Sir Ronald Charles, K.C.B., C.M.G., D.S.O.; Lt.-Col. Lord Dudley Gordon, D.S.O.; Mr. H. H. Berresford (President, Joint Iron Council); Sir William Larke, K.B.E.; Sir John Duncanson (Commercial and Technical Director, British Iron and Steel Federation); Sir Charles Goodeve, O.B.E., F.R.S. (Director, British Iron and Steel Research Association); Sir Alfred Egerton, F.R.S. (Secretary, Royal Society); Sir Peirson Frank (President, Institution of Civil Engineers); Mr. J. W. Gardom (President, Institute of British Foundrymen); Dr. Harold Hartley (President, British Cast Iron Research Association); Mr. Ellis Hunter (President, British Iron and Steel Federation); Mr. G. F. Laycock (President, Institution of Mining and Metallurgy); Dr. H. Moore, C.B.E. (President, Institution of Metallurgists); Dr. G. B. Waterhouse (Professor Emeritus of the Massachusetts Institute of Technology); and Dr. R. Durrer (Switzerland).

The loyal toast having been honoured, the Rt. Hon. John Wilmot, M.P. (Minister of Supply), proposed the toast of:

"*The Iron and Steel Institute*
and
the Iron and Steel Industry."

In doing so, he said: As a Minister who is merely a politician and a business man, you may surmise how honoured I am at the opportunity of addressing this learned technical and scientific assembly, for I understand that this Institute is the forum for all interested in the technical and scientific sides of this very great industry. Your membership is now world-wide, and, although you are reaching the age of discretion—I believe that you are now 77 years old—the outlook of this Institute, judged by all that it says and does, is youthful, vigorous, and thrustful, and its single object is to press forward along the path of knowledge in this field; and, if I may say so with homage and respect, your President has set a shining example by his own brilliant career. (*Applause.*) The latest example of that is to be found in the most interesting and informative Address which he delivered to you yesterday, and which I have had the privilege of reading, on the subject of technical education. It is a milestone.

Rightly or wrongly, this is not the occasion for a political speech, but I believe you will agree with me that in a free country it is proper that there should be more than one point of view. However many points of view there may be on a number of matters, at any rate I think we shall agree upon the tremendous importance of your industry in our national economy. Despite the incursion of newcomers—unfledged, some of them; I speak of the new light alloys and plastics—this is a steel age. This Institute has a tremendous reputation, and I should like to take this opportunity on behalf of His Majesty's Government of paying a tribute to the work which this Institute did towards the successful conclusion of the war.

I am not qualified to speak in detail of the magnificent achievements in your field, but I had the honour to be Parliamentary Secretary to the Ministry of Supply during part of the war, and I learned enough to realize the magnitude of your achievement, for instance, in the design of new steels to meet the exacting new demands of the war, and in grappling with the not easy problems arising from the acute shortage of some of the alloying materials formerly regarded as essential to certain qualities of steel. You did grand work in simplifying specifications, without which that vast volume of production would not have been possible, and in devising new methods of operational technique. All of this was a contribution to victory which only those with greater knowledge than I possess can accurately assess. It is a record for which we should be grateful and of which you should be proud.

I think that this Institute and its members have, however, a no less important part to play in the future. Whatever may be the changes that lie ahead, one thing is certain, and I ask you to believe it: Their object is to secure the highest possible scientific and technical achievement. To that end this body has a great contribution to make, and it will make it.

We have emerged from the war with glory. We are battered, we are crippled, but we are still alive. We have come into a new and a rapidly changing world, a somewhat uncomfortable and unfamiliar world; but it is exciting, it is challenging, and it is adventurous. Material progress would appear to us in some moods to have outstripped our development in the international field and elsewhere. Revolutionary developments are taking place in many fields. We have defeated the greatest threat to human freedom which we have ever faced, and we have won the war; but there is still much to be done to consolidate the peace.

The aim of us all, I am sure, was never better summed up than by the late President Roosevelt when he used those remarkable words about this being the age of the common man. Our object is to secure a continually and progressively rising standard of living for all, everywhere; and I am sure that this object can only be rapidly and successfully attained by the successful labours of scientific and technical bodies such as this. This is a scientific age, and you who work in the scientific and technical field have the future of mankind in your hands. It is not enough to keep going as before. For us in this land it is not enough just to keep up with others; we have to struggle to maintain our technical superiority in those fields which are peculiarly our own.

This industry has had a hard time. It has been hampered by long depressions between the wars, by restriction of its normal development and by the sudden abnormalities of development forced upon it by the necessities of war. By common consent, what is now needed is a large-scale programme of modernization and development to meet exacting needs and modern conditions. I am certain that the effort which will be required, an effort which must be successful, for the nation depends upon it, will give very full scope to your members. I feel sure also that under the guidance of the great man who is your new President you will devote yourselves whole-heartedly to this task.

I am aware that in some fields there may be some difference of opinion between us (*laughter*), though not so great, perhaps, as you may think; but in the field which we are in to-day we are more

fortunate. We have a common object to pursue —the attainment of technical perfection, complete knowledge, and mastery of those mysterious substances which are called iron and steel.

I wish that I could venture a little further into these technicalities. You know how fascinating, seductive, and alluring they are to laymen. I have done my best to try to understand the difference between iron and steel. (*Laughter.*) I thought at one time that I knew what that difference was, but greater wisdom brings more disillusionment. I thought I knew that iron was a chemical element, and that steel was an association of that element with carbon, and sometimes with other alloying materials. In my innocence, therefore, I assumed that pig iron did not contain carbon. However, when I became acquainted more closely with some wise men in the Ministry of Supply, and having, as I have, the advantage of old and close friendships in the iron and steel industry, I was told quietly but firmly, though in the most friendly manner, that in fact it did happen occasionally that pig iron contained more carbon than did steel. (*Laughter.*) Since then, I have been very reticent on this subject!

I understand, from reading the excellent technical papers which you are kind enough to send me, that you have broken down the homogeneous, solid piece of steel, which I liked to think of as the most solid thing in the universe, into a collection of mere crystals built up into lattices and frames, and that you are now devoting yourselves, fantastic though it may seem to outsiders—but not, of course, to you and me (*laughter*) —to the mysterious happenings which take place on the boundaries between the lattices and the frameworks and the crystals. I am very proud of myself for having got so far, and I shall not go any further. (*Laughter.*) You will fully appreciate, however, the wealth of scientific and technical knowledge that must have been brought together in the past, and that must be obtained in the future if we are to carry this great industry forward along the lines of its magnificent traditions.

This body is essential to the iron and steel industry, and its existence is a proof of the co-operation between science and industry. There is in this industry what is not, I regret to say, universal—a fine old, deep-rooted tradition of the pooling of information and scientific knowledge. In future I trust that these arrangements will be even more fully possible. Your members in industry and outside must work in complete harmony and communion, and there must be the fullest possible interchange of ideas and knowledge for the benefit of the industry as a whole.

I have had the privilege of seeing some of the discussion on the dearth of recruitment on the metallurgical side, and I can assure you of the most whole-hearted and consistent support of the Government in any schemes you may suggest to improve that situation. It seems to me that men of scientific bent should naturally find a peculiar fascination in that side of the industry, for it combines the pursuit of pure science with the practical application of scientific knowledge. Your industry has recognized the importance of the technician and the scientist, and has had the wisdom and the foresight to give him his head in industry. It also gives an outlet to individuals on that side to attain the highest managerial and directing posts. Ample scope exists in this industry for young men to rise to high positions; and therefore I believe that the solution of this particular problem in the industry is largely a matter of publicizing your requirements. I should be very glad to help. You must show that there is a path from pure science in our schools and universities and technical colleges to the practice of applied science in the day-to-day work of your industry.

I should like once more to pay tribute to the very close co-operation between yourselves in industry and yourselves in the academic world. This could not be better typified than in the person of your President. It is tremendously important, and that is why I harp upon it. In some of our industries this co-operation is lacking, or is at any rate not fully developed. Your industry is in a more fortunate position, and I congratulate you upon that fact.

From lack of technical knowledge, I regret that I am not able to do full justice to this toast, but I am, I assure you, fully conscious of the extent to which the whole future prosperity and security of this nation depend upon a strong, efficient, and scientifically-able steel industry, and also of the extent to which this depends upon the individual technical and scientific attainments of your members. With those thoughts in mind, it gives me great pleasure to propose the toast of The Iron and Steel Institute and of your President, Dr. Desch. (*Applause.*)

The PRESIDENT (Dr. C. H. Desch, F.R.S.), said: On behalf of The Iron and Steel Institute, I have to thank the Minister of Supply for his eloquent and admirable speech in proposing the toast of the Institute, and on my own behalf to thank him for his kind remarks about myself. We are glad at this time, after the close of the war, to be able to resume functions of this kind, and to see so large a gathering of our friends and colleagues. The Iron and Steel Institute, although, of course, a British Institute, and connected with the iron and steel industry in Great Britain, has nevertheless for many years had a strongly international character, and we are glad that we have so many oversea friends among us to-day.

The Minister has said that this is an industry in which there is a very free interchange of opinion. I think that there are very few industries in which secrecy plays so small a part. As soon as any invention is developed in the iron and steel industry, it is as a rule communicated to some scientific body, most often to this one, and is made public; what protection is needed is obtained through the patent law and not by the maintenance of secrets. There are one or two small branches in which some of the heads of firms imagine that they have secrets of their own, but that is because they have not looked at the current text books, where they would find those secrets. (*Laughter.*)

The Minister has very tactfully refrained from saying anything about the industrial future. It is rumoured that he has special knowledge on this subject (*laughter*), and I have no doubt that those who are sitting here feel that the sword of Damocles is suspended just above their heads; but on this occasion we will refrain from looking up! (*Laughter.*)

He has spoken of the very great efficiency of the industry. I think that we can claim, with the long history of the development of iron and steel in this country behind us, that at present we have reached a very high state of efficiency. It would be possible, of course, to go about the country and find a few very antiquated-looking works. On the other hand—I have not consulted the Minister on this point, and I do not know whether he has paid many visits to works—I think that we could take him to a number of plants which would bear comparison with plants in any part of the world. I think we can also claim that in the development of the industry on the scientific side, this country has played a part equal to that of any country in the world. The earliest inventions and discoveries originated here, and although, of course, since then a number of our competitors have caught up with us and have developed their own very excellent research organizations, nevertheless at the present time we are making contributions to the knowledge of iron and steel of the very first importance. Some of those, of course, had to be kept confidential during the war and are now gradually being released; but before long it will be seen, I think, how very great a contribution to the knowledge of iron and steel has been made here, even within the last few years.

In the very excellent and interesting introduction to the subject of metal physics which we have had from the Minister (*laughter*), he has reminded us that we are concerned not only with manufacture on a large scale but, in our various laboratories, with studying the arrangement of atoms in the metal. We are reaching a stage where many of the properties of the industrial products of the iron and steel industry can be deduced from an intimate knowledge of the physical structure of the crystals of which those metals are built up.

The Minister has spoken of the relations between the Government and the industry and the scientific side. I should like to take the opportunity of expressing the indebtedness of this and other industries to the Department of Scientific and Industrial Research for the very liberal view which it has taken of the relations between science and industry. (*Applause.*) We sometimes complain that Government departments are given to a good deal of red tape; but since the institution of the Department of Scientific and Industrial Research at the time of the last war, the freedom from red tape of that department has been very remarkable. We have had scientific men at the head of it. Sir Edward Appleton is known to all of us as one of the most distinguished of our scientific men, and he also holds an official position in which he is able to explain to the authorities what is really needed by industry on the scientific side.

Those relations have been very happy. The arrangement of having industrial research associations under the auspices of the D.S.I.R. has proved to be very useful. In visiting other countries, I have found that they have on the whole been inclined to envy the admirable organization which has been set up in that way. The new British Iron and Steel Research Association was set up only last year. It was a development, of course, of the Iron and Steel Industrial Research Council which existed before. The organization is now somewhat more elaborate, and we look forward to a very active programme of research in that field.

"*The Guests.*"

Continuing, the President said: I have now to propose the toast of our guests. We have on this occasion a large number of guests, many of them very distinguished; and now that means of transport have improved we have been able to receive a number of oversea guests. (*Applause.*) It has been characteristic of The Iron and Steel Institute that we have been very largely an international body. Although our meetings have mainly been held in this country, we have had occasion to visit a number of other countries to hold our Autumn Meetings for the reading and discussion of papers, and for visiting works. We are now able to resume those relations interrupted during the war.

It is, of course, quite impossible for me to mention by name all the distinguished guests whom we have with us on this occasion, but I should like to mention at any rate the countries from which they come—the United States of America,

Australia, France, Belgium, Poland, Holland, Spain, Switzerland, and Sweden. (*Applause.*) In addition, we have the representatives of many of the leading scientific and technical societies of our own country. I regret that the President of the Royal Society, who is the official head of science in this country, although he had expected to be here, had at the last moment to decline our invitation, but we have the Secretary of the Royal Society present, Sir Alfred Egerton. In any scientific body such as this we have to acknowledge the leadership of the Royal Society, one of the oldest-established scientfic bodies in the world. We have with us also the Presidents and Secretaries of several of the other Institutions.

I should like to refer to a few of our distinguished guests, and particularly those from overseas. Among those from the United States we have Dr. Waterhouse, who yesterday evening delivered a most admirable Address, the first of a series initiated to commemorate Dr. Hatfield, to whom the various Research Committees of the iron and steel industry owe so much. (*Applause.*) Dr. Hatfield was an intimate friend of many of us over many years, and his enthusiasm was largely responsible for the success of the whole scheme of Research Committees set up in the course of the first world war.

From France we have an old friend in M. Des Aubrys, and a young one in Dr. Bastien, both of whom have made excellent contributions to the scientific side of metallurgy. Dr. Bastien has taken part in our discussions during the last two days. I should also like to mention the presence of Dr. Durrer, of Switzerland, who has been known to many of us for many years as one of the greatest authorities on the technical aspects of the industry. (*Applause.*) From Sweden we have a considerable contingent. I shall have occasion to refer to His Excellency the Swedish Minister in a few moments, but I should like to mention now the presence of Dr. Tigerschiöld and Count Kalling, representatives of the great Swedish steel industry. (*Applause.*) Dr. Tigerschiöld is the technical head of that great body, Jernkontoret, and is always very welcome here. He has been here many times, and many of us have had the opportunity of meeting him in his own country. Jernkontoret occupies, of course, an extremely high position in the history of the industry, and next year it will be celebrating its 200th anniversary. Some of us hope to have the opportunity of taking part in those celebrations in Stockholm and of renewing our acquaintance with the industry of Sweden, an extremely progressive country.

Dr. Tigerschiöld spoke at our meeting yesterday. We thought that we had had considerable difficulties in our industry owing to the shortage of certain raw materials, but I gather from him that some of the difficulties experienced in Sweden were greater than any with which we have had to deal. I had never heard before of firing steel furnaces with bales of straw. When I was at Sheffield University we had a 2½-ton open-hearth furnace, and had occasional runs with it. We used to run it with a gas-producer fired with coal, but on one occasion the local sanitary authority asked whether we would take a load of cinders recovered from the refuse destructor and try that. We put it into the producer and obtained, of course, a blue flame instead of a yellow one, and the steel melter told us that it was hopeless; but in fact it was the hottest heat we ever turned out. Directly after that, however, the same authority came to us and asked us to take another fraction from the destructor. This consisted of potato peelings. I felt that I could not ask our steel melter to make steel from potato peelings! In Sweden, apparently, they can make steel using straw. I feel some sympathy with the managers who had to work with such a low-grade fuel!

I have to couple this toast with the name of one of our distinguished guests, His Excellency the Swedish Minister, M. Björn Prytz. I have been sitting next to him during this Luncheon. I have always found that in Sweden I had less of the feeling of being in a foreign country than anywhere else, in spite of the fact that I have no knowledge of Swedish. Wherever we went, to a works or to a scientific society, we always found people who could speak English perfectly. If I had not known that His Excellency was the Swedish Minister, I should not have detected that he was not an Englishman.

The relations between Sweden and England in the iron and steel industry date from a long time ago. I lived for many years in Sheffield, and for a very long time in Sheffield it was considered that if you wanted to make a really good steel you must start with a Swedish raw material. Sweden has the advantage of exceedingly pure ores, and its simple method of smelting led to the production of an extremely pure iron which avoids the contamination which occurs in ordinary processes of operation. Sweden has thus great natural advantages, but it does not owe its high position in the industry entirely to those natural advantages; it owes it also to the great scientific skill of the men who control the industry. We are greatly indebted to many Swedes for the progress that has been made in the development of iron and steel, over a long period.

I was interested to hear from Dr. Tigerschiöld that before the great development of iron and steel in this country, Sweden supplied 35% of the world's steel, and that now it supplies only 1%, yet its actual production has increased. That simply means that the development in other countries has been very large. We do not, of course, look to Sweden for the production of very large tonnages of steel,

but I think we shall find a good many people, particularly in Sheffield, who, if they have to make a special product, like to start with a Swedish material. The relations between our two countries have been exceedingly friendly, and it is a great pleasure to us to be able to renew them. It is therefore particularly appropriate that when I am proposing the Toast of the Guests, and we have guests here from a number of countries, we should be able to couple the toast with the name of His Excellency the Swedish Minister. (*Applause.*)

His Excellency M. BJÖRN G. PRYTZ (the Swedish Minister), who responded, said: I was somewhat surprised when I was told that my name would be coupled with the toast of the guests, and I wondered what could have secured me this honour. It certainly is not any achievements in the iron and steel field on my part, nor even any scientific knowledge which could be expressed in those felicitous terms with which the Minister of Supply surrounded his own deep knowledge. (*Laughter.*) I take it that in coupling this toast with my name, the President perhaps wished to indicate in a tactful way that my countrymen are among the most numerous of the oversea guests who have with avidity availed themselves of the kind hospitality of The Iron and Steel Institute, and not only with avidity but possibly with a certain amount of greed. (*Laughter.*) We, in Sweden, have been cut off for so long from free communication with the rest of the world that an opportunity of this kind is particularly appreciated by my countrymen in all fields, and not least in the iron and steel industry. Perhaps the President also had in mind the long and fruitful co-operation between The Iron and Steel Institute and the corresponding body in Sweden, which is picturesquely known as the Iron Office of Sweden.

In any case, I should like to congratulate you—it is so long since I found myself in so distinguished a company of scientists—on the fact of having as your President not only a great man of science but also an orator.

In Sweden we have a habit of saying after a meal "tack för matin." That means "thank you for the food." It sounds very materialistic, but it arises from the fact that centuries ago we were a very poor nation whose food was very meagre. We mixed the bark of trees with our bread, and to receive food was something for which to be grateful. We took a warm welcome and pleasant company for granted, and we gave thanks for that which was scarce and difficult to obtain. To-day we have had a charming feast and we are duly grateful, but we are not going to say "tack för matin," in extending to the President our grateful thanks for this Luncheon. It is rather the warm welcome and the good fellowship and the renewal of friendships which we have missed during the war years for which we wish particularly to thank you.

The Iron and Steel Institute has always been a great forum for the exchange of new ideas and experiences in the steel world. In the true liberal tradition of this great Empire, it has periodically brought together under its hospitable roof the steel interests of the world for the exchange of new ideas and new knowledge in the art of steelmaking. The Institute itself has never been either niggardly or tardy in publishing for the benefit of the world at large the scientific and practical results of British research. That is the hospitality for which we thank you, and which we are grateful to find resumed after the barren years of the war.

During recent years, circumstances have forced our technicians to work along very different lines. The warring countries have achieved a quantitative expansion such as no one would have believed to be possible. They have perhaps had to neglect costs for the time being, but they have undoubtedly learned many lessons as to what can be achieved, lessons which will stand them and all of us in good stead in the future. Those countries like my own, which have been cut off from supplies, have, on the other hand, had to learn lessons of economy in their use, and have on their part made discoveries and developments from which the steel industry as a whole will, I hope, also benefit, thanks not least to the opportunity for the exchange of ideas which the hospitality of The Iron and Steel Institute so generously provides.

It would not be fitting for me, as a stranger, to comment on the political and organizational developments which seem to be impending within the British steel industry, nor would I dare to rush in where not only angels but also Ministers fear to tread. (*Loud laughter.*) I may perhaps, however, be permitted to leave two thoughts with you. One is this: Whatever may be the expressed policy of Governments here or in other countries, countries who are both your customers and your competitors (and it is perhaps cheering that they are often the same people), the industry everywhere in Europe finds itself in the same period of flux and change and readjustment to the demands of the community as that in which you find yourselves, with the same uncertainties as to how far present sacrifices can be justified by the hope of future gains. In France, in Czechoslovakia, in Sweden, in Luxemburg, and the other steel-producing countries of Europe we are all under different political labels, struggling with new plans and projects, facing change and readjustment to a post-war world. Is it not perhaps possible to draw some comfort from the fact that these difficulties are simultaneous and universal, and some hope that we may in the end find

solutions which will enable us all to serve the needs of reconstruction without losing the initiative for which the men of steel in all countries have always been renowned, and sacrificing such individual advantages as our countries possess?

The other thought that I would leave with you is the conviction that whatever may be the outcome of the relations of industry to Government and to the community, whatever may be the restrictions and regulations which we may have to accept in other ways, we shall continue through such great institutions as this to maintain the free exchange of ideas, experiences, and research for the benefit of our industries and of mankind. (*Applause.*) In this sense I would ask you to drink to the prosperity of The Iron and Steel Institute, its members, and its President, Dr. Desch. (*Applause.*)

Presentation of Papers.

A list of the papers included in the programme of the Meeting will be found in Table I. The eleven papers marked with an asterisk were printed in the No. II. volume of the *Journal* for 1945. Correspondence on them will be found in the present volume. The following were presented for verbal discussion:

Table I.—*Complete List of Papers Included in the Programme of the Meeting.*

Foundry Practice Sub-Committee: "The Manufacture of Some Thin-Walled Steel Castings, with Notes on the Influence of Pouring Speed." (Paper No. 19/1946 of the Steel Castings Research Committee (submitted by the Foundry Practice Sub-Committee).) (pp. 519 P–534 P.)

S. O. Agrell: "Mineralogical Observations on Some Basic Open-Hearth Slags." (pp. 19 P–55 P.)

C. R. Barber: "The Design and Performance of Some Commercial Optical Pyrometers of the Disappearing-Filament Type." (Paper No. 18/1946 of the Steel Castings Research Committee (submitted by the Foundry Steel Temperature Sub-Committee).) (pp. 171 P–188 P.)

R. A. Cresswell: "The Tinning of Cast Iron." (pp. 157 P–169 P.)

W. Davies and W. J. Rees: "British Bonding Clays." (Paper No. 17/1946 of the Steel Castings Research Committee (submitted by the Moulding Materials Sub-Committee).) (pp. 117 P–125 P.)

W. Davies and W. J. Rees: "British Resources of Steel Moulding Sands.—Parts 6 to 10." (Paper No. 16/1945 of the Steel Castings Research Committee (submitted by the Moulding Materials Sub-Committee).) (pp. 71 P–116 P.)

W. Davies and W. J. Rees: "The Hot-Strength Characteristics of Moulding Sands." (Paper No. 15/1945 of the Steel Castings Research Committee (submitted by the Moulding Materials Sub-Committee).) (pp. 61 P–70 P.)

C. H. Desch, F.R.S., D. O. Sproule, and W. J. Dawson: "The Detection of Cracks in Steel by Means of Supersonic Waves." (Paper No. 17/1946 of the Alloy Steels Research Committee (submitted by the Hair-Line Crack Sub-Committee).)
Section 1.—"Introductory." By C. H. Desch, F.R.S.
Section 2.—"The Supersonic Flaw Detector." By D. O. Sproule.
Section 3.—"The Application of Supersonic Testing to Steelworks Problems." By W. J. Dawson.

F. Fancutt: "The Effects of Different Methods of Pretreating Iron and Steel Before Painting." (Paper No. 17/1946 of the Corrosion Committee (submitted by the Protective Coatings Sub-Committee).) (Special Report No. 31.)

W. E. Goodrich: "Overheating and Burning of Nickel–Chromium–Molybdenum Steel." (Paper No. 20/1946 of the Alloy Steels Research Committee.)

C. Hulse and R. J. Sarjant: "Problems in Fuel Efficiency."

A. H. Jay and K. W. Andrews: "Note on Oxide Systems Pertaining to Steel-Making Furnace Slags." (pp. 15 P–18 P.)

F. László: "Tessellated Stresses.—Part IV." (pp. 207 P–228 P.)

H. J. Merchant: "Some Aspects of the Overheating of Steel Drop-Forgings."

A. Preece, A. Hartley, S. E. Mayer, and J. Nutting: "The Overheating and Burning of Steel." (Paper No. 18/1946 of the Alloy Steels Research Committee.)

K. A. Pyefinch: "Methods of Assessment of Anti-Fouling Compositions." (Paper No. 16/1946 of the Corrosion Committee (submitted by the Marine Corrosion Sub-Committee).) (pp. 229 P–243 P.)

F. C. Thompson and L. R. Stanton: "The Effect of Oxygen on the Isothermal Transformations of Steel, and a Suggested Test for Burning." (Paper No. 19/1946 of the Alloy Steels Research Committee.)

M. Tigerschiöld: "Fuel Problems in the Swedish Iron and Steel Industry."

N. H. Turner and F. A. Gray: "Fuel Utilization in Iron and Steel Works."

J. Woolman and H. W. Kirkby: "Some Experiments on Overheating." (Paper No. 21/1946 of the Alloy Steels Research Committee.)

W. J. Wrażej: "Local Heating in Plain Carbon Steels." (pp. 189 P–193 P.)

* These papers will be found in the No. II. volume of the *Journal* for 1945 on the pages indicated.

Wednesday, May 1st:

Morning Session:

"Fuel Problems in the Swedish Iron and Steel Industry." By M. Tigerschiöld.
"Problems in Fuel Efficiency." By C. Hulse and R. J. Sarjant.
"Fuel Utilization in Iron and Steel Works." By N. H. Turner and F. A. Gray.

The above papers were discussed jointly.

Afternoon Session:

"The Detection of Cracks in Steel by Means of Supersonic Waves." By C. H. Desch, F.R.S., D. O. Sproule, and W. J. Dawson.
Section 1.—"Introductory." By C. H. Desch, F.R.S.
Section 2.—"The Supersonic Flaw Detector." By D. O. Sproule.

Section 3.—"The Application of Supersonic Testing to Steelworks Problems." By W. J. Dawson.

Thursday, May 2nd :

Morning Session :

"Some Aspects of the Overheating of Steel Drop-Forgings." By H. J. Merchant.

"The Overheating and Burning of Steel." By A. Preece, A. Hartley, S. E. Mayer, and J. Nutting. (Paper No. 18/1946 of the Alloy Steels Research Committee.)

"Overheating and Burning of Nickel–Chromium–Molybdenum Steel." By W. E. Goodrich. (Paper No. 20/1946 of the Alloy Steels Research Committee.)

"The Effect of Oxygen on the Isothermal Transformations of Steel, and a Suggested Test for Burning." By F. C. Thompson and L. R. Stanton. (Paper No. 19/1946 of the Alloy Steels Research Committee).

"Some Experiments on Overheating." By J. Woolman and H. W. Kirkby. (Paper No. 21/1946 of the Alloy Steels Research Committee.)

The above papers were discussed jointly.

Papers for the Autumn Meeting, 1946, Included in the Present Volume.

It has been necessary to include in the present volume certain papers which are to be presented at the Autumn Meeting, 1946, and which would normally have been printed in the No. II. volume for 1946; they are listed in Table II.

Table II.—*Papers for the Autumn Meeting, 1946, Included in the Present Volume.*

K. Balajiva, A. G. Quarrell, and P. Vajragupta : "A Laboratory Investigation of the Phosphorus Reaction in the Basic Steelmaking Process." (Paper No. 34/1946 of the Ingot Committee.)
J. H. Andrew, H. Lee, A. K. Mallik, and A. G. Quarrell : "The Removal of Hydrogen from Steel." (Paper No. 22/1946 of the Alloy Steels Research Committee.)
R. H. Baulk and M. W. Thring : "A Heat-Flow Meter for Use in Furnaces."

REPORT OF COUNCIL FOR 1945.

THE Council submit this, their Annual Report and Statement of Accounts for the year 1945, to Members for their approval at the Seventy-Seventh Annual General Meeting of The Iron and Steel Institute. Information up to 31st March, 1946, has been included in some sections of the Report.

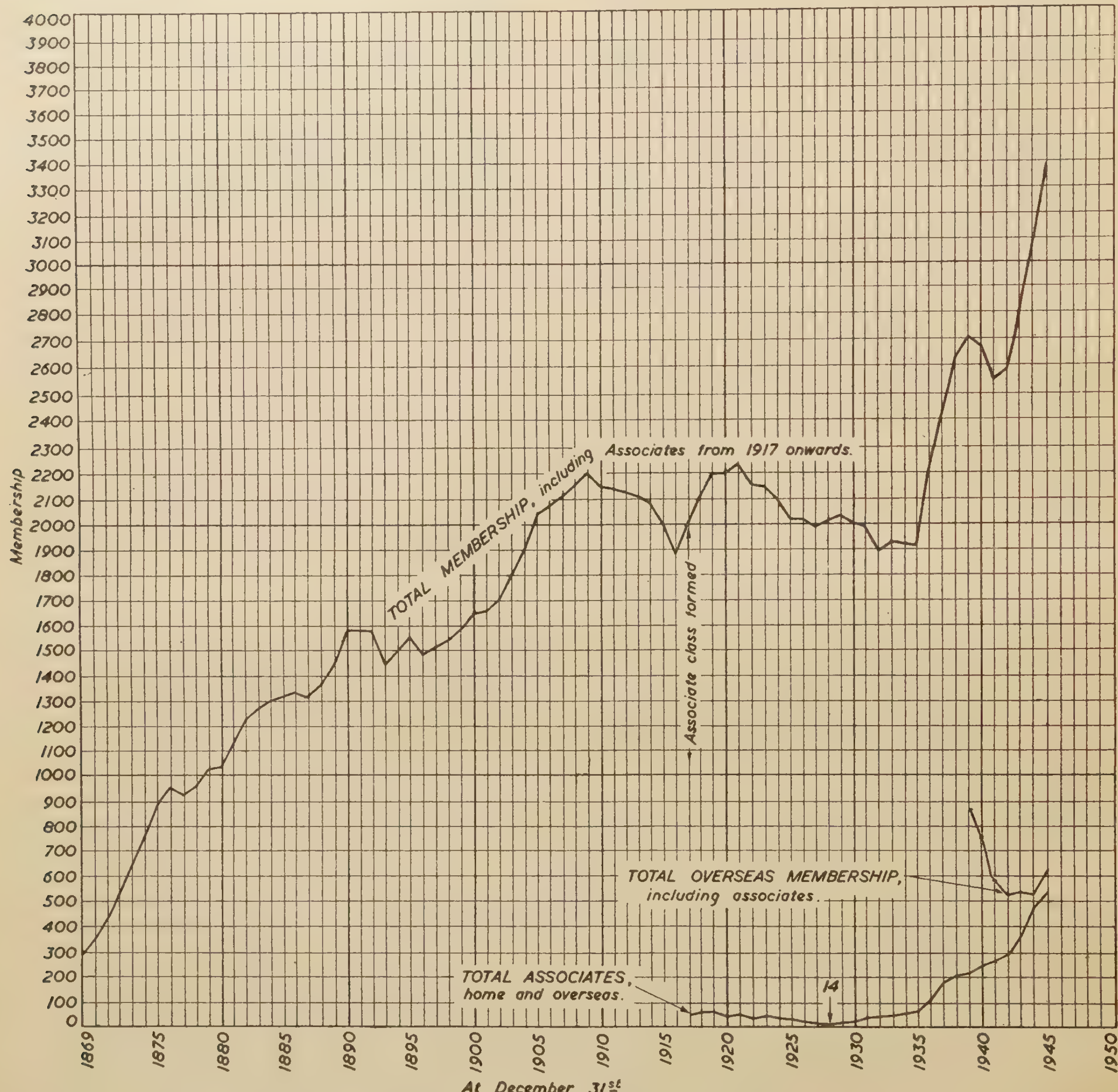


FIG. 1.—Variation in Membership since the Foundation of the Institute in 1869.

The year was made memorable by victory. Members of the Institute and the various branches of the iron and steel industries with which the majority are connected contributed materially to this successful result of six years of war. The year saw also the beginning of the difficult period of transition to peace; some progress was made,

but time must elapse before normal conditions are achieved.

The Institute has emerged from the war stronger in every respect. Membership has increased by 25% and the financial position has been consolidated.

Roll of the Institute.

Membership at the end of the year totalled 3356, an increase of 322, or 10%, over the record figure of the previous year. Particulars are given in Tables I., II. and III. and in Fig. 1.

Table I.—*Membership at 31st December*, 1945, *and Preceding Six Years.*

At 31st December:	1939.	1940.	1941.[1]	1942.	1943.	1944.	1945.
Patron	1	1	1	1	1	1	1
Hon. Members	15	14	15	14	12	13	16
Life Members	68	67	60	60	64	65	67
Ord. Members [2].	2407	2336	2213	2213	2354	2482	2736
Associates	213	248	262	295	369	473	536
Total	2704	2666	2551	2583	2800	3034	3356

[1] Revised.
[2] The above figures include six Members for 1942, seven for 1943, nine for 1945 and eight for the other years whose names were retained in the List of Members in an honorary capacity by order of the Council.

The current Roll of Members does not include 118 Members and 22 Associates who have been placed on suspense lists.

Thirty-seven deaths were reported during the year and 26 Members resigned. Two hundred and eighty-seven Members and 129 Associates were newly elected or reinstated.

Table II.—*Joint Membership with The Institute of Metals at* 31*st December*, 1945.

	Home Members.		Overseas Members.		Total.	
	Ordinary.	Joint.[1]	Ordinary.	Joint.[1]	Ordinary.	Joint.[1]
Patron	1	...	...	...	1	...
Hon. Members	7	3	5	1	12	4
Life Members	39	8	16	4	55	12
Ord. Members	1571 [2]	609	397 [3]	159	1968	768
Total (Members)	1618	620	418	164	2036	784
Associates	189	305	19	23	208	328
Total (classified)	1807	925	437	187	2244	1112
Total Membership	...	...	...	...	**3356**	

[1] Members who are also Members of The Institute of Metals.
[2] Includes eight Members whose names were retained in the List of Members in an honorary capacity by order of the Council.
[3] Includes one Member whose name was retained in the List of Members in an honorary capacity by order of the Council.

Obituary.

The Council regret to record the deaths of the following thirty-four Members which occurred during the year 1945 :

Barclay, A. C. (Glasgow) . . ?
Bendix, Carl A. (London) . . 7th February.
Bengough, Dr. G. D., F.R.S. (London) . . . . . 22nd January.
Bevan, Trevor (Shotton) . . 2nd April.
Bird, Major T. G., D.S.O. (Newcastle-on-Tyne) . . . 7th May.
Brameld, T. W. (Rotherham) . 1st January.
Brooks, S. H. (Fallowfield, Manchester) . . . . 16th December.
Bulmer, R. (Shotley Bridge, Co. Durham) . . . . 18th September.

Table III.—*Home and Overseas Membership*, 1939 *to* 1945.

At 31st December:	1939. Class.	1939. Totals.	1940. Class.	1940. Totals.	1941. Class.	1941. Totals.	1942. Class.	1942. Totals.	1943. Class.	1943. Totals.	1944. Class.	1944. Totals.	1945. Class.	1945. Totals.
Patron	1		1		1		1		1		1		1	
Hon., &c., Members :		1		1		1		1		1		1		1
Home	3		4		5		5		5		6		10	
Overseas	12		10		10		9		7		7		6	
Life Members :		15		14		15		14		12		13		16
Home	40		40		40		39		43		44		47	
Overseas	28		27		20		21		21		21		20	
Ordinary Members :		68		67		60		60		64		65		67
Home	1622		1673		1698		1753		1883		2017		2180	
Overseas	785		663		515		460		471		465		556	
Associates :		2407		2336		2213		2213		2354		2482		2736
Home	71		208		227		261		332		438		494	
Overseas	42		40		35		34		37		35		42	
Totals :		213		248		262		295		369		473		536
Home	1837		1926		1971		2059		2264		2506		2732	
Overseas	867		740		580		524		536		528		624	
Total Membership		**2704**		**2666**		**2551**		**2583**		**2800**		**3034**		**3356**

CANTLEY, Colonel The Hon. T. (New Glasgow, Nova Scotia)	?
CHARBONNEL, H. L. (Leatherhead, Surrey)	9th May.
CROSSLEY, A. (Sheffield)	?
ELLIS, Sir WILLIAM (Sheffield)	4th July.
EVERITT, C. K. (Sheffield)	6th February.
HARRISON, F. (Richmond, Surrey)	2nd April.
HENDERSON, JAMES (Fetcham, Surrey)	20th November.
HESKETT, J. A., jun. (Huntly, New Zealand)	19th September.
HOYLAND, G. (Penistone)	?
KESSLER, Dr. G. A. (Ijmuiden, Holland)	21st August.
LLOYD, H. D. L. (Stretton, Shropshire)	20th December.
LYSAGHT, W. R., C.B.E., D.L. (Chepstow, Monmouthshire)	27th April.
MACDIARMID, Sir ALLEN CAMPBELL (London)	14th August.
MCBEAN, A. D. G. (Wolverhampton)	23rd September.
MCCAFFERY, R. S. (New York, U.S.A.)	12th June.
PRICE, Dr. L. E. (Birmingham)	?
RANDLES, Sir JOHN S. (Keswick, Cumberland)	11th February.
ROBINSON, C. S. (Youngstown, Ohio, U.S.A.)	22nd July.
SMEETON, J. A. (London)	24th June.
SUMMERS, HENRY H. (Chester)	25th January.
SUTCLIFFE, E. R. (Edenbridge, Kent)	16th May.
SYKORA, VLADISLAV (Prague, Czechoslovakia)	22nd November.
TAYLOR, ROBERT (Oldham)	30th May.
WELLS, J. A. E. (Sheffield)	4th September.
WILLIAMS, Colonel PENRY (Middlesbrough)	26th June.
WILSON, FRANCIS (Pinner, Middlesex)	5th December.

The deaths of the following three Members took place earlier than 1945, but were not previously reported :

BOWEN J. C. (Kenton, Middlesex)	20th December, 1944.
GEER, Baron LOUIS DE (Leufsta Bruk, Sweden)	1925.
WHYTE, G. S. (Kenosha, Wisconsin, U.S.A.)	16th December, 1944.

Sir William Ellis and Mr. W. R. Lysaght were Past-Presidents of the Institute, Dr. Sykora was an Honorary Vice-President, and Mr. Henderson was a Past-President, Bessemer Gold Medallist and Honorary Member. Dr. Bengough was Chairman of the Marine Corrosion Sub-Committee. An obituary notice of Dr. Bengough appeared in the No. II. volume of the *Journal* for 1944, and of the three Past-Presidents in the corresponding volume for 1945.

HATFIELD MEMORIAL LECTURE FUND.

A Lecture Committee was formed under the Trust Deed consisting of Professor J. H. Andrew and Dr. J. I. O. Masson, M.B.E., F.R.S., representing Sheffield University, Dr. C. H. Desch, F.R.S., and Sir Lawrence Bragg, F.R.S., representing the Royal Society, and Mr. K. Headlam-Morley and Dr. C. Sykes, F.R.S., representing the Institute.

FINANCE.

(*The Statement of Accounts for* 1945 *is attached to this Report.*)

General Fund Balance Sheet.—The Balance Sheet is presented in the usual form.

General Fund Income and Expenditure Account.—Receipts from subscriptions and sales of publications were higher than the record figures of the previous year. After allocation to reserve and suspense accounts, the excess of income over expenditure transferred to the Balance Sheet was £415.

Trust Funds.—The financial position of the Trust Funds was well maintained.

Investments.—The value of the investments of the General and Trust Funds at the end of the year was £82,689 (an increase of £3499), or £11,473 in excess of their cost at which they are taken into the Balance Sheets.

House Fund and Industrial Subscriptions.—Income from special subscriptions was £4672. The Council acknowledge with thanks receipt of new subscriptions from Davy and United Engineering Co., Ltd., Head Wrightson & Co., Ltd., and Partridge Jones & John Paton, Ltd., and wish to take this opportunity of again expressing their thanks to the following subscribers: Edgar Allen & Co., Ltd.; Ashmore, Benson, Pease & Co., Ltd.; Babcock and Wilcox, Ltd.; Bairds and Scottish Steel, Ltd.; Baldwins, Ltd.; Arthur Balfour & Co., Ltd.; Frederick Braby & Co., Ltd.; Bradley and Foster, Ltd.; The Briton Ferry Steel Co., Ltd.; Broken Hill Proprietary Co., Ltd.; Burnell & Co., Ltd.; The Butterley Co., Ltd.; Bynea Steel Works, Ltd.; Colvilles, Ltd.; Consett Iron Co., Ltd.; The Darlington Forge, Ltd.; The Darwen and Mostyn Iron Co., Ltd.; Darwins, Ltd.; Dorman, Long & Co., Ltd.; English Steel Corporation, Ltd.; Thos. Firth and John Brown, Ltd.; General Refractories, Ltd.; Gillette Industries, Ltd.; Guest Keen Baldwins Iron and Steel Co., Ltd.; Guest, Keen & Nettlefolds, Ltd.; J. J. Habershon & Sons, Ltd.; Hadfields, Ltd.; N. Hingley & Sons, Ltd.; William Jessop & Sons, Ltd.; Kayser, Ellison & Co, Ltd.; The Kennedy Press, Ltd.; The Kettering Iron and Steel Co., Ltd.; The Lancashire Steel Corporation, Ltd.; The Llanelly Steel Co. (1907), Ltd.; John Lysaght, Ltd.; McCall & Co. (Sheffield), Ltd.; The Millom and Askam Hematite Iron Co., Ltd.; The Mond Nickel Co., Ltd.; Neepsend Steel and Tool Corporation, Ltd.;

Newton Chambers & Co., Ltd.; Samuel Osborn & Co., Ltd.; The Oughtibridge Silica Firebrick Co., Ltd.; The Park Gate Iron and Steel Co., Ltd.; The Patent Shaft and Axletree Co., Ltd.; Raine & Co., Ltd.; Round Oak Steel Works, Ltd.; Simon-Carves, Ltd.; Skinningrove Iron Co., Ltd.; Walter Somers, Ltd.; The South African Iron and Steel Industrial Corporation, Ltd.; South Durham Steel and Iron Co., Ltd.; South Wales Siemens Steel Association; The Stanton Ironworks Co., Ltd.; The Steetley Co., Ltd.; John G. Stein & Co., Ltd.; Stewarts and Lloyds, Ltd.; John Summers & Sons, Ltd.; Tata, Ltd.; Taylor Bros. & Co., Ltd.; Richard Thomas & Baldwins, Ltd.; The Tinsley Rolling Mills Co., Ltd.; The Union Steel Corporation (of South Africa), Ltd.; The United Steel Companies, Ltd.; The Upper Forest and Worcester Steel and Tinplate Works, Ltd.; Vickers, Ltd.; The Wellman Smith Owen Engineering Corporation, Ltd.; The Welsh Plate and Sheet Manufacturers' Association; Whitehead Iron and Steel Co., Ltd.; The Woodall-Duckham Vertical Retort and Oven Construction Co. (1920), Ltd.

Changes on the Council.

(*To* 31*st March*, 1946.)

At the Autumn Meeting the President announced that Dr. C. H. Desch, F.R.S., had been unanimously nominated to succeed him at the Annual General Meeting in 1946.

During the year ending 31st March, 1946, Sir Peter Brown, Mr. Fred Clements, Mr. E. J. Fox and Sir William Larke, K.B.E., were nominated Honorary Vice-Presidents, and Mr. W. J. Dawson, Mr. G. H. Latham and Mr. R. Mather Vice-Presidents.

Mr. D. F. Campbell (Davy and United Engineering Co., Ltd.), Mr. R. A. Hacking (Dorman, Long & Co., Ltd.), Dr. J. W. Jenkin (Tube Investments, Ltd.), Sir Arthur Matthews, O.B.E. (Thos. Firth & John Brown, Ltd.), and Mr. C. R. Wheeler (Guest Keen Balwins Iron and Steel Co., Ltd.) were elected Members of Council.

Sir John Duncanson (Commercial and Technical Director, the British Iron and Steel Federation) and Sir Charles Goodeve, O.B.E., F.R.S., D.Sc. (Director of Research, the British Iron and Steel Research Association), accepted invitations to be Honorary Members of Council.

The following also agreed to serve as Honorary Members of Council during their presidencies of the societies named, in succession to their predecessors in the Chair: Colonel P. G. J. Gueterbock, C.B., D.S.O., M.A. (Institute of Metals, following Dr. W. T. Griffiths), Mr. C. A. J. Behrendt (Lincolnshire Iron and Steel Institute, following Mr. J. N. Kilby), Mr. H. Bull (Sheffield Metallurgical Association, following Mr. A. A. Munro), Captain H. Leighton Davies (Swansea and District Metallurgical Society, following Mr. O. J. Thomas), Dr. J. W. Donaldson (West of Scotland Iron and Steel Institute, following Provost J. Tennent), Mr. Ambrose Firth (Sheffield Society of Engineers and Metallurgists, following Mr. F. Wardrobe), and Mr. J. H. Patchett (Cleveland Institution of Engineers, following Mr. L. Wright).

In accordance with Bye-Law No. 10, the names of Vice-Presidents and Members of Council due to retire at the Annual General Meeting in 1946, were announced at the Autumn Meeting in 1945, but Sir William Larke, K.B.E., having become an Honorary Vice-President and Mr. W. J. Dawson a Vice-President, Dr. A. McCance, F.R.S., and Mr. E. F. Law retire in their places. The list of those retiring is accordingly as follows:

Vice-Presidents.—Mr. J. R. Menzies-Wilson, Mr. C. E. Lloyd and Dr. A. McCance, F.R.S.

Members of Council.—Professor J. H. Andrew, Mr. W. B. Baxter, Mr. Gerald Steel, Mr. E. F. Law and Mr. I. F. L. Elliot.

No other Members having been nominated up to one month before the Annual Meeting, the retiring Members are presented for re-election.

Meetings.

Annual Meeting.

The Annual Meeting was held at The Institution of Civil Engineers, Great George Street, London, S.W.1, on Wednesday and Thursday, 11th and 12th July, 1945, with sessions at 10.30 A.M. and 2.30 P.M. on the first day and at 9.45 A.M. on the second. Mr. Arthur Dorman (President) was in the Chair on the Wednesday; on Thursday, Dr. C. H. Desch, F.R.S. (Senior Vice-President) presided in the President's unavoidable absence. Nine papers were discussed at the meeting.

A luncheon for Members at the Connaught Rooms, London, on 12th July was well attended, over 400 Members and guests being present.

Autumn Meeting.

The Autumn Meeting was held at the Chartered Surveyor's Institution, 12 Great George Street, London, S.W.1, on Thursday and Friday, 22nd and 23rd November, 1945, with Mr. Arthur Dorman (President) in the Chair. The sessions commenced at 10.30 A.M. and 2.30 P.M. on the first day, and at 10 A.M. on the second. Seven papers were discussed.

Publications.

The Journal.—Two volumes of the *Journal* were published in respect of 1945. The No. I. volume contained nineteen papers, including six published under the auspices of the Joint Research Com-

mittees of the Institute and the British Iron and Steel Research Association and one Andrew Carnegie Research Report, and the No. II. volume contained eighteen papers, of which three were Joint Research Committee papers. These papers are listed in the Proceedings of the May and Autumn Meetings, respectively.

In 1939 it had been decided that the *Journal* should be issued monthly as from 1st January, 1940, in a larger size, but this change was postponed on the outbreak of war. The Council have decided, subject to conditions permitting, to issue the *Journal* monthly from the beginning of 1947, and as a preliminary step to use a larger format during 1946. Eleven papers issued during January and February, 1946, in the old style have been included in the No. II. volume for 1945; correspondence on these papers will be printed in the 1946, No. I. *Journal.*

The Bulletin of The Iron and Steel Institute was published monthly during the year; as usual, it was reprinted as Section II. of the *Journals* issued for the corresponding periods. The *Bulletin* is supplied free of charge to Members on application; the subscription rate to non-members is 30*s.* per annum ($6 to members of the American Iron and Steel Institute, the American Institute of Mining and Metallurgical Engineers and the American Society for Metals).

Translation Service.—Translations of fifty-two foreign technical papers were included in the Institute's Translation Series; they are obtainable by Members at 10*s.* each (5*s.* for each additional copy of the same translation). The Council wish to record their appreciation of the collaboration received from a number of Companies, Research Associations, and Government Departments.

Joint Library and Information Department.

Joint Library.

Although demands for the loan of books and periodicals showed a slight decrease, due, no doubt, to the termination of the war and the change-over to peace-time conditions, the Council are gratified that the sphere of usefulness of the Joint Library continues to extend and that Members are availing themselves more and more of its organization. During the year 6752 publications were borrowed, as compared with 6953 in 1944. A list of additions made to the Library is issued quarterly and copies will be sent to Members on request.

Collaboration with The Institution of Civil Engineers and the Science Library.

The valuable collections of scientific works included in the Science Library and the Library of The Institution of Civil Engineers are available for consultation or loan under certain conditions.

Information Department.

The number of enquiries dealt with during the past year again increased. Members seeking information on technical subjects are invited to avail themselves of the service provided.

Bessemer Gold Medal.

The Bessemer Gold Medal for 1945 was awarded to Mr. Harold E. Wright, Chief Metallurgist of Messrs. Dorman, Long & Co., Ltd., in recognition of his valuable contributions over many years to the improvement of the technique of iron and steel manufacture.

The Bessemer Gold Medal for 1946 has been awarded to Mr. J. S. Hollings, C.B.E., in recognition of his distinguished services in encouraging technical improvement in the manufacture of iron and steel.

Andrew Carnegie Medal.

No award of the Andrew Carnegie Medal was made during the year.

Williams Prize.

Two Williams Prizes have been awarded for 1945, one to Dr. R. Jackson for his paper on "The Application of Radiography to the Improvement of Foundry Technique," and the other to Mr. T. F. Pearson for his paper on "The Improvement of the Citric-Acid Solubility of Basic Open-Hearth Slags containing Fluorspar." The papers will be found in the No. I. and No. II. volumes, respectively, of the *Journal* for the year.

Andrew Carnegie Research Scholarship.

No grant was made by the Council during 1945.

The Worshipful Company of Blacksmiths.

In response to an invitation from the Worshipful Company of Blacksmiths the Council nominated Dr. C. H. Desch, F.R.S., and the Hon. R. G. Lyttelton to represent the Institute on the Court of Assistants.

Presentations.

The Council wish to record their thanks to the Board of The United Steel Companies, Ltd., for the presentation of a portrait of the late Mr. James Henderson (Past-President, Honorary Member) by Mr. Oswald Birley.

They also thank all Members and authors who have presented books and papers to the Library.

Education.

The Committee referred to in the last Report has now been fully constituted as the "Joint Committee on Metallurgical Education"; in addition to the Institute, the following societies are represented: The Institution of Mining and Metallurgy, the Institute of British Foundrymen, The Institute of Metals and the Institution of Metallurgists.

The primary function of the Committee is to advise the Councils on all matters connected with the education of metallurgists.

National Certificates in Metallurgy.

Good progress was made in the establishment of National Certificates in Metallurgy, and courses are now being operated by a number of technical colleges.

Institution of Metallurgists.

The new "Institution of Metallurgists" was registered in November, 1945, and applications for membership of this professional Institution in the classes of Fellow, Associate and Licentiate are now invited. The Council, jointly with the Council of The Institute of Metals, have agreed to assist the new Institution by providing accommodation and the services of secretarial staff; and they extend to it cordial wishes for the future.

Relations with Other Societies and Technical Institutions.

Friendly relations were maintained with scientific societies and technical institutions in Great Britain, the Dominions and allied and neutral countries.

Co-operation with The Institute of Metals.

Collaboration with The Institute of Metals was continued on the same basis as last year. A third of the Members of the Institute are also Members of The Institute of Metals.

Affiliation with Local Societies.

The Council are pleased to announce that as from 1st January, 1946, affiliation has been arranged with four more important local societies, namely:

Cleveland Institution of Engineers.
Leeds Metallurgical Society.
Newport and District Metallurgical Society.
Swansea and District Metallurgical Society.

Affiliation with the following was announced last year:

Lincolnshire Iron and Steel Institute.
Sheffield Society of Engineers and Metallurgists.
Staffordshire Iron and Steel Institute.

The societies retain their complete independence, but have agreed to provide facilities for Members of the Institute in the districts in which they operate on terms which, it is believed, will prove mutually advantageous.

Co-operation with Local Societies.

The Council record their pleasure at the continued friendly relations existing with the following societies on the same basis as in previous years:

Ebbw Vale Metallurgical Society.
Manchester Metallurgical Society.
Sheffield Metallurgical Association.
West of Scotland Iron and Steel Institute.

Meetings with other Societies.

For the period from 1st May, 1945, *to 31st March,* 1946.

The following Joint Meetings were held with Local Societies (up to 31st March, 1946):

Wednesday, 24th October, 1945: Manchester Metallurgical Society and The Institute of Metals.

Place and Time: The Engineers' Club, Albert Square, Manchester, at 6.30 P.M.

Chairman: Dr. W. T. Griffiths, President of The Institute of Metals.

Lecture: "The Application of Radiography to The Improvement of Foundry Technique," by Dr. R. Jackson.

Saturday, 10th November, 1945: Scottish Branch of the Institute of British Foundrymen and the Association of Mining Electrical-Mechanical Engineers.

Place and Time: Royal Technical College, Glasgow, at 3.0 P.M.

Chairman: Mr. Alexander Marshall, President of the Scottish Branch of the Institute of British Foundrymen, supported by Dr. A. McCance, F.R.S., Vice-President of The Iron and Steel Institute, and Mr. C. S. Buyers, President of the Association of Mining Electrical-Mechanical Engineers.

Paper: "High-Tensile Alloy Steel Castings," by Mr. J. B. F. Jackson.

Tuesday, 27th November, 1945: Lincolnshire Iron and Steel Institute.

Place and Time: Technical School, Cole Street, Scunthorpe, at 7.30 P.M.

Chairman: Mr. C. A. J. Behrendt, President of the Lincolnshire Iron and Steel Institute.

Paper: "Sinters and Sintering.—Part I.," by Dr. H. L. Saunders and Dr. H. J. Tress.

Tuesday, 4th December, 1945: Sheffield Metallurgical Association and Sheffield Branch of the Institute of British Foundrymen.

Place and Time: Sheffield Metallurgical Club, 198 West Street, Sheffield, at 7 P.M.

Chairman: Mr. A. A. Munro, President of the Sheffield Metallurgical Association.

Paper: "Mould and Core Paints and Washes, and Parting Powders," by Dr. W. J. Rees.

Monday, 17th December, 1945 : Cleveland Institution of Engineers.

Place and Time : Cleveland Scientific and Technical Institute, Corporation Road, Middlesbrough, at 6.30 P.M.

Chairman : Mr. J. H. Patchett, President of the Cleveland Institution of Engineers.

Paper : " Some Design and Operating Features of a New Blooming Mill," by Mr. G. A. V. Russell and Mr. G. W. Fox.

Wednesday, 9th January, 1946 : Ebbw Vale Metallurgical Society.

Place and Time : The Rational Hall, Ebbw Vale, at 6.45 P.M.

Chairman : Mr. W. J. S. Roberts, Chairman of the Ebbw Vale Metallurgical Society.

Address : " Refractories—the Limiting Factor in Open-Hearth Practice," by Dr. J. H. Chesters.

Tuesday, 29th January, 1946 : Lincolnshire Iron and Steel Institute.

Place and Time : Technical School, Cole Street, Scunthorpe, at 7.30 P.M.

Chairman : Mr. C. A. J. Behrendt, President of the Lincolnshire Iron and Steel Institute.

Paper : " Some Design and Operating Features of a New Blooming Mill," by Mr. G. A. V. Russell and Mr. G. W. Fox.

Under the Affiliation Scheme Members were invited to take part in many meetings of Affiliated Local Societies, amongst them the following :

Monday, 15th October, 1945 : Sheffield Society of Engineers and Metallurgists.

Place and Time : The University, St. George's Square, Sheffield, at 6.30 P.M.

Chairman : Mr. F. Wardrobe, President of the Sheffield Society of Engineers and Metallurgists.

Lecture : " An Application of the Spectrograph and Spekker Absorptiometer to the Microchemical Analysis of Steel," by Lt.-Commander J. Convey, Ph.D., and Mr. E. J. Vaughan.

Thursday, 18th October, 1945 : Staffordshire Iron and Steel Institute.

Place and Time : Technical College, Dudley, at 6 P.M.

Chairman : Dr. J. E. Hurst, President of the Staffordshire Iron and Steel Institute.

Presidential Address ; " Residual Elements and Dissolved Gases in Cast Iron," by Dr. J. E. Hurst.

Thursday, 15th November, 1945 : Staffordshire Iron and Steel Institute.

Place and Time : Victoria Hotel, Wolverhampton, at 7 P.M.

Chairman : Dr. J. E. Hurst, President of the Staffordshire Iron and Steel Institute.

Film : " Heavy Forgings," presented by Mr. S. H. Thorpe.

Saturday, 19th January, 1946 : Swansea and District Metallurgical Society.

Place and Time : Royal Institution, Swansea, at 6.30 P.M.

Chairman : Captain H. Leighton Davies, President of the Swansea and District Metallurgical Society and Vice-President of The Iron and Steel Institute.

Paper : " Instrument Control in Open-Hearth Practice," by Mr. Talfryn Davies.

Monday, 18th February, 1946 : Sheffield Society of Engineers and Metallurgists.

Place and Time : Royal Victoria Hotel, Sheffield, at 6.15 P.M.

Chairman : Mr. F. Wardrobe, President of the Sheffield Society of Engineers and Metallurgists.

Lecture : " The Future of Co-operative Research in Iron and Steel," by Sir Charles Goodeve, O.B.E., D.Sc., F.R.S.

Saturday, 23rd February, 1946 : Swansea and District Metallurgical Society.

Place and Time : Royal Institution, Swansea, at 6.30 P.M.

Chairman : Captain H. Leighton Davies, President of the Swansea and District Metallurgical Society and Vice-President of The Iron and Steel Institute.

Paper : " Some Aspects of Rolling," by Dr. H. Ford.

Saturday, 9th March, 1946 : Swansea and District Metallurgical Society.

Place and Time : Guildhall, Swansea, at 6.45 P.M.

Chairman : Captain H. Leighton Davies, President of the Swansea and District Metallurgical Society and Vice-President of The Iron and Steel Institute.

Lecture : " Some Problems of the Metallic State," by Sir Lawrence Bragg, F.R.S.

RESEARCH.

British Iron and Steel Research Association.

As previously reported, the British Iron and Steel Research Association took over responsibility for the industry's co-operative research activities from The Iron and Steel Industrial Research Council as from 1st January, 1945. The Institute collaborated with the Research Association during the year on the same basis as previously with the Research Council.

Satisfactory arrangements for future collaboration have been made. The Research Association will during 1946 assume responsibility for work hitherto done by the Institute's Joint Research Committees and the Institute will undertake a number of duties on behalf of the Research Association, including the provision of library and information services and the publication of papers and reports. Substantial expansion of the departments concerned will be required.

Preparatory to these changes the constitution and activities of the Joint Research Committees and their Sub-Committees were reviewed. The Steel Castings Research Committee was dissolved

as from 31st December, 1945, and new arrangements were made for the continuance of the work under the direction of the Steel Castings Divisional Panel of the Research Association; the Heterogeneity of Steel Ingots Committee was renamed the Ingots Committee; in the case of this Committee and of the Alloy Steels Research Committee and Corrosion Committee a number of changes were made in the programmes of research and lists of Sub-Committees.

The following is a list of the Joint Research Committees and of their Sub-Committees, corrected up to 31st December, 1945. The number of meetings recorded in 1945 was 70 (56 in 1939; 59 in 1940; 64 in 1941; 75 in 1942; 62 in 1943; 79 in 1944):

Alloy Steels Research Committee: Chairman, Mr. W. J. Dawson. Established June, 1934. Meetings held during 1945: three.

Thermal Treatment Sub-Committee: Chairman, Mr. P. B. Henshaw. Established January, 1936. Meetings held during 1945: three.

Hair-Line Crack Sub-Committee: Chairman, Mr. H. H. Burton. Established July, 1938. Meetings held during 1945: three.

Special Aero-Components Sub-Committee: Established July, 1940. Meetings held during 1945 (not recorded).

Corrosion Committee: Chairman, Mr. W. J. Dawson. Established July, 1928. Meetings held during 1945: three.

Atmospheric Corrosion Sub-Committee: Chairman, Mr. T. Henry Turner. Established June, 1944. Meetings held during 1945: three.

Protective Coatings Sub-Committee: Chairman, Mr. T. M. Herbert. Established January, 1936. Meetings held during 1945: two.

Marine Corrosion Sub-Committee: Chairman, Professor J. E. Harris. Re-formed November, 1938. Meetings held during 1945: three.

Sub-Committee on the Corrosion of Buried Metals (working in collaboration with the Committee on Soil Corrosion of Metals and Cement Products of The Institution of Civil Engineers): Established October, 1937. No meetings held during 1945; activities carried on by correspondence.

Industrial Waters (Corrosion) Sub-Committee: Chairman, Dr. J. W. Jenkin. Established May, 1945. Meetings held during 1945: three.

Methods of Testing (Corrosion) Sub-Committee (previously sub-committee IS/28/1, Drafting Committee for Protective Coatings of Iron and Steel, of the British Standards Institution): Chairman, Dr. J. C. Hudson. Established November, 1945. Meetings held during 1945: one.

Heterogeneity of Steel Ingots Committee (formerly the Committee on the Heterogeneity of Steel Ingots): Chairman, Mr. H. H. Burton. Established May, 1924. Meetings held during 1945: three.

Ingot Moulds Sub-Committee: Chairman, Mr. R. H. Myers. Established November, 1934. Meetings held during 1945: two. (Stresses in Moulds Panel, none.)

(*Sub-Committee on the Physical Chemistry of Steel-making.* Established 1938. No meetings held during 1945. Dissolved.)

Liquid Steel Temperature Sub-Committee: Chairman, Mr. E. W. Elcock. Established March, 1929. Meetings held during 1945: three.

Sub-Committee on Gaseous and Non-Metallic Inclusions (including the Oxygen Sub-Committee): Chairman, Mr. W. W. Stevenson. Established January, 1936: title changed February, 1944. Meetings held during 1945: two. (Chemists' Panel, four.)

Inclusions Sub-Committee: Chairman, Mr. W. J. Dawson. Established November, 1936. Meetings held during 1945: three.

Standard Methods of Analysis Sub-Committee: Chairman, Dr. E. Gregory. Established September, 1939. Meetings held during 1945: six.

Steel Castings Research Committee: Chairman, Mr. W. J. Dawson. Established November, 1934. Meetings held during 1945: four.

Moulding Materials Sub-Committee: Chairman, Dr. W. J. Rees. Established March, 1936. Meetings held during 1945: three.

Foundry Practice Sub-Committee: Chairman, Mr. F. Cousans. Established May, 1938. Meetings held during 1945: four.

Foundry Steel Temperature Sub-Committee: Chairman, Mr. D. A. Oliver. Established December, 1941. Meetings held during 1945: two.

Side-Blown Converter Practice Sub-Committee: Chairman, Dr. T. P. Colclough. Established September, 1943. Meetings held during 1945: four.

Refractories Panel (reporting through the Side-Blown Converter Practice Sub-Committee to the Open-Hearth Refractories Joint Panel of the British Refractories Research Association and the British Iron and Steel Research Association): Chairman, Dr. R. J. Sarjant. Established December, 1943. Meetings held during 1945: two.

Metallurgical (Steel Castings) Sub-Committee: Chairman, Mr. W. J. Dawson. Established June, 1944. Meetings held during 1944: four.

Staff.

The Council wish again to put on record their appreciation of the services rendered by the staff. Mr. A. E. Chattin, Assistant Secretary, completed twenty years' service with the Institute.

Honours Conferred on Members.

(*To 31st March*, 1946.)

The Council tender their warmest congratulations to the following Members of the Institute for honours and appointments received during the period under review:

Aitchison, Dr. L.—Appointed to the first Chair of Industrial Metallurgy at Birmingham University.

Archer, Robert S.—Awarded Sauveur Achievement Medal of the American Society for Metals.

AUSTIN, G. WESLEY.—Elected to the Goldsmiths Professorship of Metallurgy at Cambridge University.

BEHRENDT, C. A. J.—Elected President of the Lincolnshire Iron and Steel Institute.

BIERS, H.—Served during the war on the Technical Advisory Committee on Alloy and Special Steels set up by the Department of Munitions and Supply of the Canadian Government.

BULL, H.—Elected President of the Sheffield Metallurgical Association.

CHESTERS, Dr. J. H.—Awarded degree of Doctor of Technical Science by Sheffield University.

CHEVENARD, Professor P.—Elected a Member of the French Academy of Sciences.

DAVIES, Captain H. LEIGHTON, C.B.E.—Elected President of the Swansea and District Metallurgical Society.

DELPORT, VINCENT.—Appointed Public Relations Officer to the Joint Iron Council.

DONALDSON, Dr. J. W.—Elected President of the West of Scotland Iron and Steel Institute.

DOREY, Dr. S. F.—Created Commander of the Order of the British Empire.

EVANS, Dr. U. R.—Appointed to the Readership in the Science of Metallic Corrosion at Cambridge University.

FAULKNER, V. C.—Elected an Honorary Member of the Czechoslovak Foundrymen's Association.

FIRTH, AMBROSE.—Elected President of the Sheffield Society of Engineers and Metallurgists.

FRANCIS, HERBERT.—Created a Member of the Order of the British Empire.

GARDOM, J. W.—Awarded the E. J. Fox Gold Medal of the Institute of British Foundrymen. Re-elected President of the Institute of British Foundrymen for a second year.

GILL, C. S.—Elected Chairman of the British Steel Founders' Association.

GOODEVE, Dr. CHARLES, F.R.S., O.B.E.—Created a Knight Bachelor.

GREEN, A. T.—Created an Officer of the Order of the British Empire.

HARDY, H. K.—Awarded the degree of Doctor of Philosophy.

HARDY, T.—Served during the war on the Technical Advisory Committee on Alloy and Special Steels set up by the Department of Munitions and Supply of the Canadian Government.

HENSHAW, P. B.—Elected President of the Crucible Steelmakers' Association.

HURST, Dr. J. E.—Made a Freeman of the Worshipful Company of Smiths.

JEFFRIES, Dr. ZAY.—Awarded the Annual Powder Metallurgy Medal of the Stevens Institute of Technology. Awarded the Francis J. Chalmer Medal of the Franklin Institute.

JENKIN, Dr. J. W.—Elected President of the Birmingham Metallurgical Society.

JONES, Sir LEWIS, M.P.—Appointed Parliamentary Commissioner to the Charity Commission.

LARKE, Sir WILLIAM, K.B.E.—Awarded the Honorary Degree of Doctor of Science at Durham University.

MCCOSH, A. K.—Elected President of the British Employers' Confederation.

PATCHETT, J. H.—Elected President of the Cleveland Institution of Engineers.

PEAT, C. U.—Appointed Parliamentary Secretary, Ministry of National Insurance.

REES, Dr. W. J.—Elected President of the British Ceramic Society.

SARJANT, Dr. R. J.—Created an Officer of the Order of the British Empire.

TIGERSCHIÖLD, MAGNUS.—Awarded the degree of Doctor, *honoris causa,* at Upsala University.

TREVORROW, J. H. L.—Created a Commander of the Order of the British Empire.

WHITE, Dr. JAMES.—Appointed Lecturer in Refractory Materials in the Department of Metallurgy, Sheffield University.

APPOINTMENT OF REPRESENTATIVES.

The following is a list of the Institute's representatives on various governing bodies and committees at 31st March, 1945:

BRITISH CAST IRON RESEARCH ASSOCIATION: Professor T. Turner.

BRITISH CORPORATION REGISTER OF SHIPPING AND AIRCRAFT, Technical Committee: Dr. A. McCance, F.R.S.

BRITISH ELECTRICAL AND ALLIED INDUSTRIES RESEARCH ASSOCIATION,
- Sub-Committee J/E, Joint Committee, Steels for High Temperatures: Dr. J. W. Jenkin; *one appointment open.*
- Sub-Committee F/J, Earthing to Water Mains: Dr. J. C. Hudson.

BRITISH IRON AND STEEL FEDERATION,
- Statistical Committee: Mr. K. Headlam-Morley.
- Films Panel: Mr. K. Headlam-Morley.

BRITISH IRON AND STEEL RESEARCH ASSOCIATION, Council: Professor J. H. Andrew, Professor G. Wesley Austin, Mr. Arthur Dorman, Mr. J. Sinclair Kerr, Dr. J. W. Jenkin, Dr. E. Gregory, Dr. W. T. Griffiths, The Hon. R. G. Lyttelton, Dr. W. J. Rees.

BRITISH REFRACTORIES RESEARCH ASSOCIATION, Council: Mr. J. Sinclair Kerr.

BRITISH STANDARDS INSTITUTION,
- General Council and Executive Committee: Mr. J. R. Beard (representing the Founder Institutions).
- Chemical Engineering Divisional Council: Mr. E. F. Law.
- Engineering Divisional Council E/-: The Hon. R. G. Lyttelton, Mr. J. Sinclair Kerr, Mr. W. B. Baxter.
- Sub-Committee IS/35/3, Malleable Steel Castings: Mr. C. H. Kain.
- Sub-Committee C/25/10, Painting of Iron and Steel: Mr. F. Fancutt, Mr. R. A. Hacking.
- Sub-Committee CEB/6/1, Concrete Blocks: Mr. W. J. Brooke, J.P.
- Technical Committee CEB/1, Cement: Mr. W. J. Brooke, J.P.
- Technical Committee CH/17, Symbols used in Diagrams of Chemical Engineering Plant: Mr. A. E. Chattin.
- Sub-Committee CH/18/2, Metallic Finishes: Mr. T. W. Whiting.
- Sub-Committee CH/18/4, Phosphate Coatings: Dr. J. C. Hudson.
- Technical Committee EL/28, Fans: Mr. A. F. Webber, Dr. A. M. Burdon.
- Technical Committee HIB/15, Pressed Steel Galvanised Rainwater Goods: Dr. A. M. Burdon.
- Iron and Steel Industry Committee IS/-: Mr. F. H. Saniter.
- Technical Committee IS/-/1, Advisory Committee on Iron and Steel: Mr. F. H. Saniter.
- Technical Committee IS/1, Co-ordination of Iron and Steel Specifications: Mr. S. Barraclough.
- Technical Committee IS/6, Steel Castings: Dr. R. H. Greaves.
- Technical Committee IS/8, Creep Properties: Mr. L. Rotherham.

Technical Committee IS/11, Galvanised Corrugated Steel Sheets: Dr. J. C. Hudson.
Technical Committee IS/15, Iron and Steel for Shipbuilding: Sir Edward J. George.
Technical Committee IS/17, Cast Iron Columns for Street Lighting: Mr. J. G. Pearce.
Technical Committee IS/28, Protective Coatings for Iron and Steel: Dr. J. C. Hudson.
Technical Committee IS/29, Tinplate: Mr. D. Luther Phillips.
Technical Committee IS/35, Cast Iron: Mr. J. G. Pearce.
Technical Committee ME/23, Indentation Hardness Testing: Mr. J. Woolman.
Technical Committee ME/25, Testing of Metal Sheets and Strip: Dr. A. M. Burdon.
Technical Committee ME/32, Engineering Symbols and Abbreviations: Dr. A. M. Burdon.
Technical Committee PAM/160, Reels and Drums for Electrical Wires: Dr. A. M. Burdon.
Technical Committee PSM/2, Welders' Goggles: Dr. C. H. Desch, F.R.S.
Solid Fuel Industry Committee, SF/-: Mr. A. F. Webber.
Technical Committee SF/1, Nomenclature and Definitions: Mr. A. F. Webber.
Technical Committee SF/2, Underfed Screw Type Stokers: Mr. A. F. Webber.
Technical Committee SF/4, Heating Stoves: Mr. A. F. Webber.
Technical Committee SF/17, Sampling and Analysis of Flue Gases: Mr. F. A. Gray.
Units and Technical Data Co-ordinating Committee: Sir Wm. Larke, K.B.E.
Conference M/4, Letter Symbols: Dr. A. M. Burdon.

City and Guilds of London Institute, Advisory Committee on Metallurgy: Dr. J. W. Jenkin.

Constantine College, Advisory Committee: Mr. E. W. Jackson.

Empire Council of Mining and Metallurgical Institutions: Mr. K. Headlam-Morley, Mr. J. Sinclair Kerr.

Engineering Public Relations Committee,
Main Committee: *appointment open.*
Executive Committee: Mr. K. Headlam-Morley.

Hatfield Memorial Lecture Committee: Mr. K. Headlam-Morley, Dr. C. Sykes, F.R.S.

Hong-Kong University, Home Committee: *appointment open.*

Imperial College of Science and Technology, Board of Governors: Dr. C. H. Desch, F.R.S.

Imperial Institute, Mineral Resources Department, Iron and Ferro-Alloy Metals Committee: Mr. K. Headlam-Morley.

Institute of Fuel, Council: Dr. R. J. Sarjant.

Institute of Physics, Industrial Radiology Group, Sub-Committee on Terminology relating to Casting Defects revealed by X-Rays: Dr. R. Jackson.

Institute of Welding,
Council and Representative of Patron Institution: Mr. K. Headlam-Morley.
Joint Library Committee (with British Welding Research Association): Mr. K. Headlam-Morley.

Institution of Civil Engineers, Committee on Soil Corrosion of Metals and Cement Products, Sub-Committee on Soil Corrosion of Metals: Dr. J. C. Hudson.

Institution of Mechanical Engineers, Research Committee on High-Duty Cast Irons for General Engineering Purposes: Dr. J. E. Hurst.

Joint Committee on Materials and their Testing: Mr. K. Headlam-Morley.

Joint Committee on Metallurgical Education: Dr. C. H. Desch, F.R.S., Mr. R. A. Hacking, The Hon. R. G. Lyttelton.

Liverpool University, Court of Governors: Sir W. Peter Rylands, Bt.

King's College, Newcastle-upon-Tyne (University of Durham), Metallurgy Advisory Committee: Mr. J. H. Patchett.

Lloyd's Register of Shipping, Technical Committee: Mr. H. H. Burton, Mr. R. A. Hacking.

National Certificates in Metallurgy Joint Committee: Mr. R. A. Hacking, Dr. J. W. Jenkin.

National Physical Laboratory, General Board: Professor J. H. Andrew, Mr. W. J. Dawson.

Parliamentary and Scientific Committee: Mr. K. Headlam-Morley.

Ramsay Memorial Laboratory, Advisory Committee: *appointment open.*

Royal School of Mines, Advisory Board: Mr. Vernon Harbord.

Royal Society, General Board for Administering Government Grants for Scientific Investigations: The President.

School of Metalliferous Mining (Cornwall), Board of Governors: Mr. J. S. Hollings, C.B.E.

Science Museum, Advisory Council: *appointment open.*

Sheffield University, Court of Governors: Sir Arthur B. Winder, J.P.

Worshipful Company of Blacksmiths, Court of Assistants: Dr. C. H. Desch, F.R.S., the Hon. R. G. Lyttelton.

[The Statement of Accounts for 1945 will be found in the following pages.]

THE IRON AND STEEL INSTITUTE.

BALANCE SHEET, 31st DECEMBER, 1945.

LIABILITIES.

1944. £	£			£	£
		Sundry Creditors :—			
	445	Office Rent, Telephone, Heating, &c.		470	
	933	Publishing (part estimated)		2,417	
	165	Salaries, Insurance and Income Tax, Staff Deductions		227	
	160	Printing and Stationery, Library Books and Postage		101	
	105	Travelling and Entertaining, Sundry Payments		122	
	43	Autumn Meeting		—	
	39	Subscriptions in Suspense		76	
1,890					3,413
		Amounts Received in Advance :—			
	108	Members' Subscriptions		184	
	155	Special Subscriptions		385	
	265	Sales of Publications		486	
528					1,055
	268	Legacy by Sir Robert Hadfield, Bart., F.R.S.		268	
	4	Accumulated Interest on Investment (Gross)		12	
272					280
—		Joint Education Committee			100
		Suspense Account as at 1st January, 1945 :—			
		Reserve for Ten-Year Index	£500		
		Add Further Transfer, 1945	50		
	500			550	
		Bessemer Gold Medal	100		
		Add Further Transfer, 1945	25		
	100			125	
	1,000	Library Account		1,000	
	2,000	Repairs and Decorations		2,000	
3,600					3,675
		Entrance Fees Reserve Fund		3,204	
		Add Further Transfer, 1945		301	
3,204					3,505
		Life Composition Fund		3,638	
		Add Compounded during 1945		89	
3,638					3,727
		General Reserve		2,000	
		Add Further Transfer, 1945		1,750	
2,000					3,750
		Iron and Steel Institute :—			
	23,882	Capital as per Last Balance Sheet		23,882	
	1,981	Accumulated Excess of Income over Expenditure ...	£2,552		
	571	*Add* Excess of Income over Expenditure for the Year ...	415		
				2,967	
26,434					26,849
£41,566					£46,354

ASSETS.

1944. £	£		£	£
		Sundry Debtors :—		
		Subscriptions in Arrear		Not valued.
	76	Publishing	99	
	3,397	Income Tax Recoverable	1,669	
	270	Sales of Publications	211	
	16	Sundries	53	
	30	Special Subscriptions	—	
	31	National Certificates in Metallurgy	—	
3,820				2,032
		Payments in Advance :—		
	200	Staff Superannuation Fund	194	
	—	Institution of Metallurgists	250	
	111	Sundries	131	
	—	Sundry Researches	100	
	645	Publishing Special Report No. 30	—	
956				675
—		Stock of Journals		Not valued.
—		Office Furniture and Library		Not valued.
1,003		Cash at Bank and in Hand		3,654
1,406		Post Office Savings Bank Deposit Account		2,966
		Legacy by Sir Robert Hadfield, Bart., F.R.S. :—		
	268	Investment at Cost per Schedule	268	
	4	Cash at Bank	12	
272				280
		(The Market value of this Investment at 31st December, 1945, was £273.)		
		Investments at Cost per Schedule :—		
29,905		General Fund		32,405
		(The Market value of these Investments at 31st December, 1945, was £36,338.)		
		Life Composition Fund :—		
		Investments at Cost per Schedule	3,685	
		Cash at Bank	42	
3,638				3,727
		(The Market value of these Investments at 31st December, 1945, was £3,956.)		
		Loan Accounts :—		
	—	Institute of Metals	39	
	—	Institution of Metallurgists	310	
	566	Joint Research Committees	241	
566				590
—		Joint Education Committee		25
£41,566				£46,354

We have examined the above Balance Sheet of the Institute and certify it to be correct.

224, Regent Street,
London, W. 1.
28th February, 1946.

Signed) W. B. Keen & Co.,
Chartered Accountants.

INCOME AND EXPENDITURE ACCOUNT FOR THE YEAR ENDED 31st DECEMBER, 1945.

INCOME

1944. £	£			£	£
		Entrance Fees ...	£270		
		Do. Companies Nominations	31		
	270			301	
	270	*Less* Transfer to Reserve Fund		301	
—					—
		Annual Subscriptions :—			
	5,568	Members, Home Current		6,022	
	110	Do. Companies Nominations		42	
	165	Do. Arrears		248	
5,843					6,312
	1,030	Members, Overseas Current		1,214	
	2	Do. Companies Nominations		5	
	251	Do. Arrears		204	
1,283					1,423
	400	Associates, Current		485	
	38	Do. Companies Nominations		5	
	12	Do. Arrears		26	
450					516
		Sales of Publications :—			
	1,296	Journals, &c.		1,795	
	157	Bulletin		74	
	549	Translations		775	
2,002					2,644
		Interest on Investments (Gross) :—			
	1,169	General Fund		1,203	
	130	Life Composition Fund		134	
	16	Bessemer Medal Fund		16	
1,315					1,353
34		Interest on Deposit Account			70
40		Sundry Receipts			89
		Institute of Metals :—			
	750	Rent Receivable		750	
	475	Contribution to Joint Library	£500		
	−50	*Less* Refund	—		
				500	
1,175					1,250
		British Iron and Steel Research Association :—			
	750	Grant for Bulletin		750	
	3,000	Grant for Secretarial Services		3,000	
	500	Grant for Information Service		500	
4,250					4,250
2,291		Balance, being Excess of Expenditure over Income carried down			2,349
£18,683					£20,256
£	£			£	£
		Special Subscriptions :—			
	3,171	Contributions received during 1945		3,106	
	1,541	Income Tax recoverable		1,566	
4,712					4,672
£4,712					£4,672

EXPENDITURE.

1944. £	£			£	£
	7,653	Salaries (including Pensions and Overtime)		7,060	
	481	Staff in H.M. Forces		461	
	1,155	War Bonus		812	
	9,289			8,333	
	150	*Less* Contribution from Carnegie Research Fund		150	
9,139					8,183
74		National Insurance			83
330		Staff Superannuation Fund			320
1,200		Office Rent			1,200
54		Repairs, Decoration and A.R.P.			142
903		Cleaning, Heating, Lighting and Water			962
389		Library Books and Binding			291
108		Office Furniture			184
68		Annual Meeting			112
49		Autumn Meeting			35
—		Local Societies			82
		Publishing Expenses :—			
	1,635	Journal : Printing and Paper		2,395	
	141	Postage		274	
	301	Advance Copies : Printing		487	
	150	Postage		111	
	477	Bulletin : Printing		419	
	60	Postage		57	
	17	Bibliographies		46	
	748	Translations Service		413	
	—	Special Report No. 30		602	
	—	Do. Postage		43	
	73	Special Publications		31	
3,602					4,878
—		Bessemer Gold Medal			12
837		Stationery and Printing			1,030
602		Postage and Receipt Stamps			670
370		Travelling and Entertainment Expenses			619
	61	Insurance		57	
	31	Do. War Damage		3	
92					60
52		Auditors' Fees for 1944			52
236		Telephone Rental and Calls			271
227		Office Disbursements and Sundry Expenses			371
—		National Certificates			162
—		Institution of Metallurgists			250
		Grants :—			
	50	British Electrical and Allied Industries Research Association		25	
	25	British Refractories Research Association		25	
	1	Joint Committee on Materials and their Testing		1	
	50	British Standards Institution		50	
	10	Mellor Memorial Fund		10	
	—	Joint Education Committee		25	
	10	Parliamentary and Scientific Committee		—	
	105	Hatfield Memorial Lecture Fund		—	
	100	Sundry Researches		151	
351					287
£18,683					£20,256
£	£			£	£
2,291		Balance brought down			2,349
		Transfer Reserve and Suspense Accounts :—			
	—	Repairs and Decorations		—	
	50	Library		—	
	50	Ten-Year Index		50	
	1,500	General Reserve		1,750	
	25	Bessemer Gold Medal		25	
1,625					1,825
		Companies Nominations :—			
	75	Entrance Fees		31	
		Subscriptions Account :			
	110	Home Members	42		
	2	Overseas Members	5		
	38	Associates	5		
				52	
225					83
571		Balance, being Excess of Income over Expenditure			415
£4,712					£4,672

THE WILLIAMS PRIZE FUND.

BALANCE SHEET, 31st DECEMBER, 1945.

LIABILITIES.

1944. £	£		£	£
2,220		Capital Value representing Market Value of £3,000 3½% Conversion Loan at 21st September, 1926, when the Fund was inaugurated ...		2,220
		Income and Expenditure Account :—		
	617	Balance as at 1st January, 1945	743	
	Add 126	*Deduct* Excess of Expenditure over Income for the Year to 31st December, 1945	74	
743				669
£2,963				£2,889

ASSETS.

1944. £	£		£	£
2,670		£3,452 15*s*. 7*d*. 3½% Conversion Loan (at cost)		2,670
		Cash at Bank :—		
	48	On Current Account	69	
	245	Post Office Savings Bank Account	150	
293				219
£2,963				£2,889

INCOME AND EXPENDITURE ACCOUNT FOR THE YEAR ENDED 31st DECEMBER, 1945.

INCOME.

1944. £		£
121	Interest on 3½% Conversion Loan	121
5	Interest on Deposit	5
—	Balance, being excess of Expenditure over Income for the year	74
£126		£200

EXPENDITURE.

1944. £		£
—	Awards	200
126	Excess of Income over Expenditure for the Year	—
£126		£200

ANDREW CARNEGIE RESEARCH FUND.

BALANCE SHEET, 31st DECEMBER, 1945.

LIABILITIES.

1944. £	£			£	£
		Sundry Creditors :—			
	90	Grants		65	
	10	Auditors' Fees		10	
100					75
	500	General Reserve		1,000	
	500	*Add* Further Transfer, 1945		500	
1,000					1,500
23		Bank Overdraft			—
	21,241	Amount of Original Fund, $100,000		21,241	
	4,441	*Add* Amounts since Capitalised per last Balance Sheet ...		4,441	
	25,682			25,682	
	4,596	*Add* Surplus Income as at 1st January, 1945 ...	5,155		
	559	*Add* Excess of Income over Expenditure for the year	602		
				5,757	
30,837					31,439
£31,960					£33,014

ASSETS.

1944. £	£		£	£
30,938		Investments at Cost per Schedule ... ... (The Market Value of these Investments at 31st December, 1945, was £38,050.)		32,188
		Cash at Bank :—		
	—	On Current Account	176	
	108	On Deposit Account	108	
	353	Post Office Savings Bank Account	362	
461				646
561		Income Tax Recoverable		180
£31,960				£33,014

INCOME AND EXPENDITURE ACCOUNT FOR THE YEAR ENDED 31st DECEMBER, 1945.

INCOME.

1944. £		£
1,238	Interest on Investments (Gross)	1,269
4	Interest on Deposits	9
£1,242		£1,278

EXPENDITURE.

1944. £		£
23	Printing Reports	16
150	Contribution to General Fund on account of Salaries	150
10	Audit Fee	10
500	General Reserve—Amount set aside	500
559	Balance, being Excess of Income over Expenditure for the Year	602
£1,242		£1,278

THE IRON AND STEEL INSTITUTE.

SCHEDULE OF INVESTMENTS AT 31st DECEMBER, 1945, SHOWING NOMINAL VALUES, COST VALUES AND PRESENT MARKET VALUES.

GENERAL FUNDS OF THE INSTITUTE.

Nominal Value. £	s.	d.	Nature of Security.	Market Value, 31st December, 1945. £	Cost Value. £
2,197	7	0	3½% War Stock	2,232	2,161
1,324	7	4	3½% Conversion Loan	1,333	1,254
447	0	0	Southern Railway 4% Debenture Stock	472	449
1,872	0	0	London & North Eastern Railway 4% 2nd Guaranteed Stock	1,722	2,150
2,241	0	0	Do. do. 4% 1st do.	2,196	2,432
2,649	4	0	2½% Consolidated Stock	2,417	1,800
1,500	0	0	Buenos Ayres Great Southern Railway 4% Debenture Stock	915	1,595
2,954	1	0	4% Consolidated Stock	3,276	3,176
437	0	0	London & North Eastern Railway 3% Debenture Stock	380	376
12,242	19	3	4% Funding Loan, 1960/90	13,804	9,512
2,000	0	0	3% Defence Bonds (Post Office Register)	2,000	2,000
2,000	0	0	3% Savings Bonds, 1955/65	2,040	2,000
2,000	0	0	Do. 1960/70	2,025	2,000
1,500	0	0	Do. 1965/75	1,526	1,500
				£36,338	£32,405

LIFE COMPOSITION FUND.

Nominal Value. £	s.	d.	Nature of Security.	Market Value	Cost Value
587	13	10	3½% Conversion Loan	623	513
493	4	4	3% Local Loans	481	467
1,330	0	0	London & North Eastern Railway 3% Debenture Stock	1,157	1,255
594	0	0	London Passenger Transport Board 4½% "A" Stock	714	638
205	15	6	3½% War Stock	212	212
681	13	0	4% Funding Loan	769	600
				£3,956	£3,685

ANDREW CARNEGIE RESEARCH FUND.

(Trustees: Sir Wm. Larke, K.B.E.; The Hon. R. G. Lyttelton.)

Nominal Value. £	s.	d.	Nature of Security.	Market Value	Cost Value
6,897	14	11	3½% War Stock	7,122	6,896
800	0	0	Do.	826	794
2,693	12	0	3½% Conversion Loan	2,855	2,007
2,642	12	0	3% Local Loans	2,577	2,527
2,250	0	0	North Eastern Electric Supply Company 3½% Consolidated Debenture Stock	2,227	2,262
1,500	0	0	Great Western Railway 4% Debenture Stock	1,612	1,204
2,000	0	0	London, Midland & Scottish Railway 4% Debenture Stock	2,060	1,693
1,312	0	0	London & North Eastern Railway 4% 1st Guaranteed Stock	1,286	881
5,000	0	0	Do. do. 4% Debenture Stock	5,150	3,540
6,000	0	0	Do. do. 3% do.	5,220	3,545
1,000	0	0	3% Savings Bonds, 1955/65	1,020	1,000
2,250	0	0	Do. 1960/70	2,278	2,250
2,813	2	7	2½% Consolidated Stock	2,567	2,339
1,250	0	0	3% Defence Bonds	1,250	1,250
				£38,050	£32,188

WILLIAMS PRIZE FUND.

(Trustees: Sir Wm. Larke, K.B.E.; The Hon. R. G. Lyttelton)

Nominal Value. £	s.	d.	Nature of Security.	Market Value	Cost Value
3,452	15	7	3½% Conversion Loan	£3,660	£2,670

BESSEMER MEDAL FUND.

(Trustees: Sir Francis Samuelson; Desmond Lysaght; The Hon. R. G. Lyttelton; N. H. Rollason.)

Nominal Value. £	s.	d.	Nature of Security.	Market Value	Cost Value
400	0	0	London, Midland & Scottish Railway 4% Debenture Stock	£412	—

HADFIELD LEGACY.

Nominal Value. £	s.	d.	Nature of Security.	Market Value	Cost Value
267	11	2	3% Savings Bonds, 1955/65	£273	£268

(*Signed*) R. G. Lyttelton.
Hon Treasurer.

(*Signed*) K. Headlam-Morley.
Secretary.

We have examined the foregoing Balance Sheets and Income and Expenditure Accounts with the Books and Vouchers of the Institute and certify them to be correct. We have also verified the balances at the Bankers and the Securities for the Investments shown above.

224, Regent Street,
London, W. 1.
28*th February*, 1946.

(*Signed*) W. B. Keen & Co.,
Chartered Accountants.

PRESIDENTIAL ADDRESS.

SCIENCE AND THE STEEL INDUSTRY.

By C. H. DESCH, F.R.S.

THE past eventful year, marking as we hope the close of one era in human history and the inauguration of another, has been significant both for the iron and steel industry and for this Institute. Although the normal conditions of industry in time of peace are far from having been restored, the urgent necessity of providing, often at very short notice and under severe handicaps, the great variety of products demanded by war on a colossal scale has passed, and our thoughts are turned towards the resumption of normal production for civilian use. In some branches of the industry the changes required involve little disturbance; in others a complete transformation. Each undertaking has its own problems to solve, and all are affected by such factors as the rising cost of fuel, but it is at least possible to assume that there will for long be no falling-off in the total demand for steel. How the means of satisfying that demand will be distributed it is too early to say. The task of replacement alone, after the widespread and utterly unprecedented destruction of the war, is vast and immediate. Bridges, buildings, and all forms of transport throughout Europe and in many regions of the East have been deliberately destroyed and can now at most yield a supply of scrap, incidentally setting new problems for the producer of steel. Continental works, owing to destruction and damage and also to the restrictions to be imposed on Germany by the Allies for military reasons, will be unable to cope with the demand, and increased calls will be made on ourselves and on those Allies whose productive capacity remains intact or has even been greatly expanded. The future of such an industry as ours will inevitably depend on the wisdom of statesmen in making such economic arrangements as will best enable each producing country to make its fullest contribution to the rebuilding of a shattered world, even should it prove necessary for some of these countries to forego advantages which they enjoy at the moment and which they may feel sorely tempted to retain. The international organizations which have been set up and are now active have many anxious problems to solve, and those concerned with the economic factors are among the most difficult. The feeling of optimism with which the League of Nations was greeted has gone, but the desperate necessity of agreement between nations has been forced upon the attention of the whole world, and in spite of international jealousies and suspicions a real effort is being made to reach solutions of the problems resulting, not only from two world wars, but from the maladjustments which were among the causes leading to those wars.

In our own country, apart from the extensive and sometimes difficult work of reconversion from production for war to normal conditions, much modernization of plant, and that on a very large scale, will be needed if we are to reach the standard of efficiency that modern engineering and technical knowledge has made possible. It was in this country that the Industrial Revolution first took place in the eighteenth century; it was here that iron and steel works were put into operation and industrial towns grew up while the Continent and America were still in the agricultural stage; it was here that new processes—the production of crucible steel, rolling by grooved rolls, puddling, the use of hot blast, the Bessemer and open-hearth steel processes, and basic working—were invented and applied. It was here, too, that the scientific foundations of steel metallurgy were laid by Lowthian Bell, Sorby, and many others. With this history of leadership, and remembering that for long the British iron and steel industry had no major competitors, it is not surprising that some plants, surviving from those times of early prosperity, should now need reconstruction, and the planned replacement of plant which falls short of the high standard of efficiency set by the best of the establishments under scientific control is one of the immediate tasks. Fully integrated plants, working on a large scale and handling their materials from the mine to the finished product, have shown their advantages, and in spite of the enormously high capital costs it is certain that they will constitute a very large proportion of the industry. But the small specialized works, employing highly skilled men on some important product of which the total tonnage is small, still has a place in the national economy, and to the student of industry the study of these relatively small undertakings, making products ranging from razors to gramophone needles and from permanent magnets for radio apparatus to engravers' tools, depending for their existence largely on a traditional standard of craftsmanship, has a fascination of its own, and

the importance of such small industries is out of proportion to their size.

In the larger metallurgical operations instrumental and even automatic controls are increasingly used, with the inevitable result of demanding less in the way of individual skill but also far less in the way of exhausting labour, often injurious to health. Conditions of labour leading to such dreadful occupational diseases as the Sheffield "grinders' rot" have been eliminated by the development of mechanical methods. The tendency of improvements in plant and processes is to lighten the burden on the individual worker and to increase his opportunities for culture and recreation, a change which should more than compensate for some loss of that traditional knack which had for so long to take the place of a scientific understanding of processes.

This consideration brings me to the main subject of my address: The services that science can render to the industry. There is no need to dwell on the importance of those services before such an audience as this. An examination of the 152 volumes of our *Journal* will show how great has been the share of this Institute in the evolution from an empirical to a highly scientific industry. I will speak only of recent events. The past year has seen the formation of the British Iron and Steel Research Association, framed on the lines of other research associations formed in accordance with the schemes of the Department of Scientific and Industrial Research. It is worth while to recall the share of this Institute in initiating co-operative research in the iron and steel industries.

It was during the first world war that the need of organized research work in metallurgy became obvious. After committees appointed by the government to consider ferrous and non-ferrous metallurgy respectively had reported on that need, this Institute took action and established five committees which reported on the state of knowledge then existing. Four of these proceeded no further, but "No. 5 Committee," with its label "Metallography, Physics, and Chemistry," was more ambitious, Dr. Stead and Dr. Rosenhain being particularly active. The first task of the Committee was a thorough overhaul of the methods for the analysis of iron and steel, and with the co-operation of a number of firms and of the National Physical Laboratory, standard steels were prepared which could be supplied with guaranteed analysis, so that works chemists could use the samples to check their own analytical results. The correspondence and interchange of samples and analyses which this involved did much to improve analytical practice in iron and steel works. However, a main difficulty in the way of obtaining uniformity was the variation in composition between different parts of the same ingot, this heterogeneity largely persisting after the ingot had been rolled into billets or plates. The emphasis on the several tasks of the Committee therefore underwent a change, and what had previously been a sub-committee now, under the name of the "Committee on the Heterogeneity of Steel Ingots" entered on a new career of activity. When the Iron and Steel Industrial Research Council was formed in 1929 that Committee became a joint responsibility of the Institute and of the Research Council. Its Chairman was the late Dr. Hatfield, and its activities owed much to his energy and enthusiasm. The same may be said of the Alloy Steels Research Committee and the Corrosion Committee, of both of which he was Chairman. The joint organization worked well. Any excessive rigidity of structure was avoided. The discussions were delightfully informal, and with the numerous sub-committees dealing with such specific questions as the improvement of methods of analysis, the prevention of hair-line cracks, the effect of inclusions on resistance to fatigue, &c., together with the active co-operation of the principal steelmaking firms, much valuable work was done. I would particularly mention the study of methods for determining the temperature of liquid steel and of estimating the oxygen in steel. With the valuable help of the National Physical Laboratory, as well as that of the industrial research laboratories, investigation of these particular problems was advanced beyond anything hitherto accomplished in this country or abroad. Makers of scientific instruments collaborated, and means for recording the true temperature of molten steel without any correction for emissivity were devised, only a very brief immersion of a sensitive thermocouple being needed. Such measurements have now become the common practice in most of the leading works.

The fourth of the Joint Research Committees dealt with steel castings. In addition to these Committees others were set up to cover particular aspects of the industry, dealing with blast-furnace, open-hearth, fuel-economy, gas-producer, and rolling-mill practice. Two series of larger meetings, the Blast-Furnace and the Open-Hearth Conferences, have been conspicuously successful in bringing together most of the men actually in charge of those departments, and being entirely private they have led to the full and frank discussion of the many problems associated with those sections of the industry. The new organization has the means of initiating and supporting research work under all of these heads, and much will be expected of it.

I must not leave the subject of the Research Committees without a tribute to Dr. Hatfield and Dr. Swinden for their share in fostering the organization in its early stages, in securing the

willing co-operation of so many industrial firms and academic departments, and in placing at the disposal of the several Committees their own wide experience of the industry. Without their help progress would have been far less rapid. Their comparatively early deaths, like that of one of our ablest investigators of corrosion, Dr. Bengough, must be attributed to the additional strain which they bore during the war years. Those of us who were in contact with them during that time know that their services to the country, although almost unknown to the general public, were invaluable, and among metallurgists their names will long be remembered.

From the much larger resources and the highly organized structure of the new Research Association we may expect a marked acceleration in the programme of research, with benefit to the industry generally, under the guidance of its distinguished Director, Sir Charles Goodeve, who comes with a high reputation gained in the war work of the Admiralty. Although some investigations hitherto undertaken mainly by the Institute will pass to the control of the Association, the relations between the two bodies are and will remain exceedingly intimate, their mutual help being essential to success.

However complete the planning of an organization for applying science to an industry may be, the results obtained depend in the last resort upon the quality of the individuals engaged in the work of research. Panels and committees have their uses: They suggest problems; they bring about collaboration between industrial undertakings and national and educational establishments; and the interchange of ideas in the course of their discussions is often a most valuable stimulus to research, but in general it may be said that committees do not make discoveries—that is the doing of individuals. A suggestion once having been made, a committee can assist most materially in providing means for investigating its value and in bringing the experience of many undertakings into a common pool, so that the final results are quite legitimately presented as a co-operative achievement. In this way the committees working under the Iron and Steel Industrial Research Council have rendered most valuable services.

An organization for research depends for its success on the quality of the investigators whose services it can command. Moreover, success in applying the results of research to industrial practice depends on the capacity of departmental managers and others—not excepting chairmen and managing directors—for appreciating and estimating at their true value the conclusions presented to them by the research workers. Hence the importance of the subject of the supply of trained metallurgists. It must be frankly confessed that in this respect the present situation in this country is disquieting. The supply of men with the requisite training and with the ability to take positions of responsibility is insufficient. The industry can, with great advantage to itself, absorb more men with the scientific habit of mind, capable of appreciating an industrial problem and of discerning the direction in which a solution is to be sought. They may be required for research work or for the control of operations on the plant, and there is no doubt that some men are better suited by temperament and inclination for the one function and some for the other, but the proper bent may not always be discerned until after a certain period of both laboratory and works experience. I have spoken of the past record of discovery and invention in the iron and steel industries of this country, and it is for us to do our best to enable that record to be continued. The Institute has had this question under active consideration during the past year, and you have seen some account of what has been done and planned in the Annual Report. The insufficient entry into the metallurgical schools of our universities is due in large part to the lack of knowledge on the part of the public of what metallurgy involves. It is the ambition of many boys, even from an early age, to become engineers, and they are able, by model-making and other activities, to acquire such a facility in some branch of engineering—such as radio transmission—as to be able, when the time comes, to enter on a course of training with some understanding of its character and possible outcome. There is at present no such approach to metallurgy, and unless a boy is immersed in a metallurgical environment through living, let us say, in Sheffield, he is unlikely to show a bias in favour of a metallurgical training. The Institute has taken active steps to remedy this state of affairs and to attract to the metallurgical profession pupils of capacity as high as that of entrants to any of the learned professions. I do not suggest that such pupils do not choose metallurgy at present, but only that too few do so. In my boyhood there was an excellent book, Pepper's "Playbook of Metals," which even then had passed through many editions and must have influenced many boys. The late Sir Robert Hadfield acknowledged his own indebtedness to it and distributed many copies to schoolboys. It is, of course, quite out of date to-day, but the Institute has undertaken to prepare publications serving the same purpose, making a popular appeal to boys and also giving to schoolmasters a survey of the openings afforded by this, one of the largest and most essential of all our industries. This work of propaganda, in the best sense, should bear fruit within a few years.

It has been felt that the means of obtaining a qualification in metallurgy, other than by graduating from a university, are insufficient. Steps

have therefore been taken to establish, with the co-operation of the Board of Education, National Certificates in the subject, and this scheme should give great encouragement to classes in those technical schools throughout the country in which metallurgy is taught. The Institution of Metallurgists has been formed with the object of certifying the qualifications, both educational and practical, of the members of metallurgical staffs. By such means as these it is hoped to encourage the entry of increased numbers of suitable candidates into courses of training for the industry. In spite of some important differences, the situation of the non-ferrous metallurgical industries is very similar to our own, and the Institute of Metals and the Institution of Mining and Metallurgy are, in various ways, associated with us in these educational efforts.

A Joint Committee on Metallurgical Education, of which I have the honour to be Chairman, has been formed by the bodies mentioned, together with the Institute of British Foundrymen. Impressed by the crying need for a larger number of trained metallurgists, the Department of Scientific and Industrial Research conducted an enquiry under the chairmanship of Dr. McCance, which arrived at a number of important conclusions. These have been discussed with professors of metallurgy, and as a result of these steps we may look forward to an alleviation before long of what is undoubtedly a serious situation.

The provision of scientifically highly trained men will continue to be in the main, as it has been in the past, the function of the universities and of the larger technical colleges associated with them. All metallurgical processes, from the preparation of the ore to the conversion of a metal or alloy into cast, rolled, or forged products, are applications of physical and chemical principles, and an understanding of those processes must be based on a sound knowledge of physics and chemistry. Early specialization, although it may furnish skilled operators of known processes, must fail to produce students with the breadth of knowledge and elasticity of mind that will be called for in order that we may not merely maintain our present standards but greatly surpass them. In the hard economic conditions which must prevail in the world for years to come, the best talent available must be secured and so trained as to be able to take advantage of new knowledge, arising perhaps in quite different fields. A good general education must form the basis of a scientific training. Within my own lifetime, mainly through the influence of the competitive scholarship system, over-specialization has become common even in schools, and it is a fallacy to suppose that the lack of breadth can be compensated for by a more intensive study of a small field. What is true of schools is also true of universities, where a tendency to narrow the field of study for honours students has become only too obvious. I commend an examination of the report * of a committee of the British Association on this question. We have even heard proposals for a one-subject university, especially for aeronautics, although such a university is a contradiction in terms. Science and industry both need educated men in the fullest sense of the word, and the lack of them cannot be compensated for by the provision of highly finished experts who know everything within a very limited range but are almost illiterate outside it. The progress of science, pure and applied, needs the fertilizing effect of contacts with other studies, now more than ever before. We have therefore to guard against the ousting of humanistic studies from college courses by the increasing growth of the demands on scientific knowledge made by enthusiastic advocates of science. It may be urged with reason that many of our university and college courses in scientific subjects include too much detail, so that there is a real risk of the student becoming unable to see the wood for the trees. The better the principles of a science are taught the greater are the opportunities for the student to acquire his knowledge of details later, and the fresher is his mind when he enters industry and has to learn the mass of facts essential to his work, which facts he would have found wearisome had they been forced upon his attention during his student career. I am not pleading for a superficial training—far from it—but I am convinced that the better the teacher the less need he has to overload his students with masses of data in order to illustrate those principles which they are to apply in their industrial career. I have elsewhere † referred to the fact that the finest ideal scheme of general education that I have seen is proposed by a humanist,‡ who, nevertheless, gives the greatest place to science, not as a single specialism, but as a foundation so solid as to bear any specialized superstructure that may be erected upon it. Such an ideal education is only for the best brains, but it is precisely the best brains that will be needed for the reconstruction of industry and of society in a shattered world. We have to see that a proportion of the ablest men available adopt metallurgy as a career, for on the progress and efficiency of the metallurgical industries depends the progress of most other industries in this machine age. There are problems of the supply of raw materials, of economies in the use of those materials which are becoming scarce, of the development

* *Advancement of Science*, 1944, vol. 3, p. 1.
† C. H. Desch, "Science and the Social Order." London, 1946: Royal Institute of International Affairs.
‡ B. Dobree, *Political Quarterly*, 1944, Oct.–Dec.

of new products, of the best utilization of labour, of distribution and of economic relations, enough to call for the help of the best men we can obtain.

So far I have spoken of men entering industry, but it must be remembered that the quality of the trained men depends in great measure upon the quality of the teachers under whom they studied. I think that all who are connected with the metallurgical departments of the universities and larger technical colleges will agree that it has been difficult of late to obtain suitable recruits to their staffs. It is essential that there should be a supply of capable young men willing to adopt an academic career even at the sacrifice of prospects in industry which may seen more glittering in perspective; young men able to take the place of their seniors when the time comes for them to retire and in the meantime to introduce into their teaching new ideas which they will have acquired from contact with workers in allied subjects. In considering education for industry this is a factor which must not be overlooked.

Metallurgy is not a fundamental science. In so far as it is a science at all, it consists in the study of physics and chemistry as applied to the special class of metallic substances. It existed as an art thousands of years before it was furnished with a scientific basis, and in some branches the skill of the experienced manual worker still counts for much. But the days when fuel economy and speed of production were not vital have passed, and scientific knowledge becomes more and more essential to production. We increasingly make use of refined methods of control, often depending on physical phenomena unknown at the beginning of the century.

Photo-electric cells, valve amplifiers, cathode-ray oscillographs, appliances for generating and receiving supersonic waves, spectrographs for both emission and absorption spectra, magnetic permeameters, X-ray apparatus for inspection and for crystal analysis, are all now familiar objects in many steelworks. It will not be long before the electron microscope takes its place beside the optical microscope, which has for eighty years rendered invaluable service. The trained metallurgist of to-day must be acquainted with a wide range of physical methods of measurement. Nor must the chemical side be forgotten, although of late it has tended to be overshadowed by the sensational advance of modern physics. We are devoting more attention to the physical chemistry of the reactions between molten metal and slag, to accurate analytical methods for the estimation of alloy elements and impurities, and to the effects of different atmospheres on metals in the course of heat-treatment. The constitution of alloys has become increasingly the province of the physicist, but as a chemist I would urge that the chemical aspect should not be overlooked and that a point of view derived from a previous training in chemistry, even in organic chemistry, may not be without value. For this reason I would deprecate any attempt to define too rigidly the qualifications of a metallurgist. Industrial establishments and research institutions should be free to recruit, as they have hitherto done, from students in allied fields of study such as physics, chemistry, and engineering; such recruitment should be made in the confidence that the knowledge and mental attitude acquired in those fields will provide a fresh approach to the problems presented by the metal industries. Metallurgy is particularly suited to be a post-graduate subject, and the heads of metallurgical departments in universities and technical colleges will, I feel sure, agree that the presence of a few such individual recruits from other sciences, engaged in senior studies and research, provides a stimulus and encouragement to students following a more orthodox metallurgical training.

I would add a note on the advantages of mobility in the course of scientific study. From medieval times onwards a period of foreign study was included in the education of scholars who had a real love of learning, and the tradition, which had never died out, became more general in the second half of the nineteenth century. Students of my own time who chose chemistry as a profession—and the same was true in other sciences—strove to spend a year or more in some Continental university, most often German. Working in a foreign laboratory under some celebrated professor, learning his technique, listening to lectures and writing one's notes in a new language, having perhaps the opportunity of visiting industrial plants, enjoying something of student life among companions as poor as oneself, all these were experiences of real value, and I feel that it is a misfortune that so few of the students of to-day enjoy those opportunities. The war of 1914–18 not only broke the tradition of semesters spent in Germany, but largely destroyed the habit of study abroad. Costs have risen, and probably most students wishing to work in a foreign laboratory will need some help from scholarships. France, Sweden, and perhaps Holland may attract some of our post-graduate students, but no doubt many will wish to cross the Atlantic and gain knowledge and inspiration in one or more of the finely equipped institutions in the United States. That involves much higher costs than the poor travelling scholar of the nineteenth century had to face, and the scholarships will for this reason have to be correspondingly more generous. It is therefore most welcome news that the munificent scheme of The Mond Nickel Company for Fellowships contemplates that at any rate a large proportion of them should be awarded for foreign travel, leaving the recipient a very free choice of the

course of study in laboratories or works to be pursued and the places to be visited. Such an elastic scheme may have most valuable results.

Not all senior students, however, will wish to go abroad. There is much to be said for a period of post-graduate work in an institution other than the university in which the first degree was taken. When the degree of Doctor of Philosophy was instituted during the first world war its object was to attract to this country overseas students who would formerly have gone to Germany. I do not think that its authors originally contemplated the award of the degree to our own students, but it soon became evident that they could not be excluded, and it is now the usual goal of a period of post-graduate study, resulting in the award of the title of Doctor without having to reach the much higher standard of the D.Sc. That the degree is so commonly taken as the result of continuing to work in the same laboratory as that in which the first degree was taken and under the same supervisors is to be regretted. The practice leads to an excessive mental inbreeding and consequent narrowness of outlook. I should like to see the regulations altered so that the Ph.D. degree should not, or should only in very special circumstances, be taken in the university or college in which the student first graduated. No doubt professors will part very reluctantly with their best students, but if their reputation as teachers and supervisors of research be high they will be receiving in return the best students trained by other professors, and the benefits will be mutual. Further, it should not be compulsory for a student wishing to undertake research work and to obtain a Ph.D. degree to spend his whole time in a university laboratory. Arrangements will certainly be made by which he can work in a national laboratory, in an establishment under a research association, or even in an industrial firm, provided that he is under a chief of known standing, recognized as qualified to act as supervisor. Both the student and the organization in which he worked would benefit by such contacts. For the higher doctorates, of course, such extramural work is already recognized and is in fact usual.

It is by no means necessary that every graduate seeking to qualify for industry should undertake research, although I believe that such a view is sometimes held. The desire to call oneself Doctor leads many young men, I am sure, to undertake work in which they are not greatly interested but which appears safe to provide them in two years with matter for a thesis, when they might be much more usefully and interestingly employed on a productive plant, gaining experience in the handling of machines and of men. We should not make a fetish of the doctorate.

We have to see that existing knowledge is applied as fully as possible to our methods of production and to meeting the continually increasing stringency of demands from users. Methods of testing, greatly improved in recent years, still call for further study if they are to yield data from which the user—I do not mean the actual customer, but the engineer or technician who has to plan the processes for manipulating the material—is to be able to make the best choice. In his desire to obtain the most suitable product the user is apt to say, like Angelo in *Measure for Measure*, "Let there be some more test made of my metal," and it is important that acceptance tests be simple and at the same time as indicative as possible of the true properties of the metal. Whilst determinations of electrical and magnetic properties give immediately the information required of them, mechanical tests are empirical and only partly or indirectly indicate the behaviour of the material in use.

The question naturally arises: Can we make use of the deeper knowledge of the nature of metals and of the constitution of metallic systems which we now possess to predict the properties of a given metal, or to devise new alloys to give a desired combination of properties? I think that an affirmative answer can be given, although much remains to be done. It is stated that Taylor and White made more than 50,000 experiments before arriving at the best composition and heat-treatment for the high-speed tool steel which created a sensation at the Paris Exhibition of 1900, when for the first time a heavy lathe was seen running with the tip of the cutting tool at a red heat. The original Japanese (Mishima) steel for permanent magnets was evidently invented as the result of a very lengthy series of trials of alloys of varied composition, probably running into many thousands. Further progress in both classes of steels has been made with less expenditure of labour and material through being based on a more systematic knowledge of constitution. Although magnetic theory is still imperfect in comparison with that of other branches of physics, it has made such progress that the latest compositions and heat-treatments of permanent-magnet steels, including cooling in a strong magnetic field, have given results far transcending those of the Japanese workers, without the long and laborious process of trial and error. Work at Cambridge and elsewhere has revealed the constitution of these complex steels and has provided useful guides to composition and heat-treatment.

For a long time further development of tool steels was on empirical lines, a little of first one element and then another being added, rather on the principles of a cookery book, until improved properties were obtained. Now, largely owing to use of the method of isothermal transformation (that is, of heating to a high temperature and then cooling to some temperature which is maintained

constant for a sufficient time, the process being repeated on other specimens at different temperatures) it has been possible to analyse the separate effects of various alloying elements on the rate of transformation on which hardening and softening depend. In the course of the war it was discovered that we had allowed ourselves an extravagant luxury in the number of different compositions of alloy steels for engineering use, and a drastic revision by the Technical Advisory Committee (which again owed so much to Dr. Hatfield) led to the number of specifications being reduced from 3000 to 83, with resultant great economy of material and also of the clerical and administrative work involved in the selection of steel for a specific and probably urgent use.

We need, however, to have much more systematic knowledge of the specific influence of alloying elements, and for this we must start with iron of the highest attainable purity. I have urged strongly that this should form an important part of the work of the National Physical Laboratory, as the institution best equipped for handling pure alloys at high temperatures and investigating their properties over the widest range. When we examine the influence of a given element in steel it is often found that the particular property studied varies regularly, often linearly, with the quantity added, so long as the metallographic constitution remains the same. However, even when the curve is linear, if extrapolated to reach pure iron it usually cuts the axis at a point different from that found when the purest iron, containing none of the element in question, is tested. This is still more evident when the cumulative effect of several alloying elements is examined. The conclusion must be that the initial effect of small additions is out of all proportion greater than that of the same element in larger quantities. This can only mean that the small addition is not distributed evenly throughout the mass of the metal but is concentrated in thin films, probably at the grain boundaries. In studying properties of this kind one is inevitably impressed by the importance in metals of the narrow region intervening between the lattices of two crystal grains. Brittleness, creep under constant load at high temperatures, corrosion under stress, ageing after cold-working, are all affected in a marked degree by the properties of this elusive intercrystalline region. Its bulk is too small to be detected by X-rays and although some of its important properties are on such a scale as to be recognizable under the highest powers of the microscope, it is not usually possible to prepare a surface by mechanical means which will preserve such minute detail. Much may be expected of the new technique, developed by Jacquet, of producing a perfect polish by electrolytic means without surface flow, and a combination of this method of preparation and the use of the electron microscope with its high resolving power may, in the next few years, bring us most valuable information. This same technique should help us greatly in the study of mechanical deformation, on which research is now exceedingly active but which would lead me too far afield to discuss to-day.

X-ray methods have furnished us with important fundamental information about metals. The sizes and arrangement of the atoms are known; from such information it is possible to deduce which elements will take their place in the lattice of the solvent metal and which will be accommodated in the interstices, a matter of moment in determining the properties of an alloy. X-ray methods also indicate the limits of solid solubility, fixed mainly by geometrical considerations, and the work of Preston and Guinier has shown how the first segregation of foreign atoms occurs in the varied series of changes known as age-hardening. If metallic masses consisted of perfect crystals the problem of predicting their mechanical strength would not be difficult. However, they are not perfect. Single crystals have an internal mosaic structure, and it has been shown that the observed mechanical properties are governed by the presence of minute dislocations or flaws which can be displaced during a change of form. A knowledge of the space lattice and of the electrical condition of the metallic atoms therefore does not take us far towards predicting the cohesive properties of a metal in mass, and we have to be content with empirical results, but this is a field in which progress is being made in both experiment and theory.

The main practical object of researches of this kind is the attainment of higher quality in the products of manufacture, due regard being paid to economy in production. If we keep a careful record of every consignment of a certain product of a works (such as rolled strip), the composition and manufacturing procedure being kept as constant as is practicable, on plotting the values of a specific property, such as tensile strength or ductility, a frequency curve is obtained, which with normal working should approximate to a Gaussian probability curve. The bulk of the results will cluster about some mean value, but there will be some falling well below it and some well above. Good practice will be indicated by the small amount of spread on each side of the maximum. The fact that some points lie on the high side shows that with the materials and processes available it is possible to reach qualities superior to the general run of the product. The reasons for failure to reach the average can often be found without difficulty—some irregularity in the working of a furnace, an accidental defect in a rolling mill, &c.—but the exceptionally high results are less easily explained and deserve inten-

sive study. The aim of scientific control in a works is not only to narrow the area of this probability curve, that is, to obtain a more uniform product, but also to shift the maximum to higher values, that is, to improve the average value of the property considered. That the curve of selling prices may not correspond with that of metallurgical quality is a point of great interest to the commercial manager but should not unduly discourage the efforts of the scientific staff.

What the economic future of the industry at home and abroad will be it is impossible at this critical time to predict. One thing is certain: There will be no room for inefficiency. If the manufacture of iron and steel in this country, with the high cost of coal and the necessity for importing so much of the raw materials, is to succeed, both the equipment and the direction of our works must be of first-class quality. No skill in finance can take the place of efficient technical direction, and we must look forward to trained metallurgists with the solid background of a good general education assuming an increasing share in the management of the great undertakings which will comprise the major part of the industry. It is for this reason that I have dwelt on the subject of education. A very considerable number of new entrants to the metallurgical profession will be needed within the next few years, and that is why the Institute, in collaboration with other bodies having similar interests, is taking an active part in improving educational facilities.

The main function of the Institute, however, is that of collecting and making available knowledge of advances in the science and practice of iron and steel production by publishing original papers and abstracts of papers published elsewhere and by the provision of its excellent library and information services. The Institute has a record of seventy-seven years of valuable work, and in this first year of peace, albeit an uneasy one, we may look forward to an increased activity, worthy of the great industry with which it is associated and of those pioneers who laid, before that industry had become world-wide, the foundations upon which it has been reared. There is no indication that the initiative and perseverance which these founders exhibited have departed, and we may hope that these qualities will be no less manifest in the period of reconstruction which lies before us.

A HEAT-FLOW METER FOR USE IN FURNACES.*

By R. H. BAULK, M.Sc., and M. W. THRING, M.A., F.Inst.P. (The British Coal Utilisation Research Association, London).

(Fig. 9 = Plate I.)

Synopsis.

The first step towards improving the flow of heat to the charge in melting furnaces is to develop an instrument that will measure the value of the heat flow at any point in the furnace under the varying conditions of operation. In particular, it was desired to be able to measure the heat transfer by radiation and convection from the flame to the charge and to the furnace walls.

The work on such an instrument has reached a stage where a practical research tool has been evolved and used to compare the heating power of different flames, to examine the effect of flame thickness upon the heat flow from the flame, and to compare the heat flow at different points along and across the flame. It has shown, for example, that measurement of the downward heat flow below the flame at its two ends gives a valuable quantitative measure of the effective flame length; in the case of very slow combustion the downward heat flow at the outgoing end is greater than at the ingoing end. It has also been shown that the heat-absorbing area of the surface of the charge is not very fully utilized either in the steel furnace or in the glass tank, the former because the flame does not cover the whole area and the latter because the cold batch is not spread out.

List of Terms and Symbols.

Cycle: The period between the instant at which the flame in a reversing furnace begins to travel in one direction and the instant at which it next begins to travel in that direction.

Half-Cycle: The period during which the flame travels solely in one direction.

Reversal: The instant at which the direction of the flame is altered.

Downward Heat Flow: The total heat transferred in the downward direction, as measured by the calorimeter facing upwards.

Upward Heat Flow: The total heat transferred in the upward direction, as measured by the calorimeter facing downwards.

Net Heat Transfer: The amount of heat absorbed by the charge (*i.e.*, the difference between downward and upward heat flows).

Incoming End of Flame: The end of the flame nearest the port through which the gases enter the furnace.

Outgoing End of Flame: The end of the flame nearest the port through which the gases leave the furnace.

Side: That extremity of a cross-flame regenerative tank furnace along which the ports are built.

End: The boundary of a steel furnace along which the ports are built.

Left Side (*of a cross-flame regenerative tank furnace*)*:* The side on the left hand of an observer facing the furnace from the feed end.†

Left End (*of a steel furnace*)*:* The end on the left hand of an observer facing the furnace from the charging side.†

Flame LR(3) : Denotes a flame travelling from the left-hand to the right-hand port with the heat-flow meter in No. 3 door.

Door Numbers: The doors of a steel furnace are numbered from left to right.

Batch: The mixture of ingredients from which glass is made.

Charge or *Stock:* The materials heated in the bath or hearth of the furnace.

Slag: The layer formed above the steel by the lime and other impurities extracted in the process of refining the charge.

Centigrade Heat Unit (*C.H.U.*)*:* The amount of heat required to raise the temperature of 1 lb. of water through 1° C. (1·0 C.H.U. = 1·8 B.Th.U.).

A = area of test-body, sq. ft.
C = coefficient of convection heat-transfer from the gases to the charge (or test-body), C.H.U./sq. ft./hr./°C.
E = absorptivity of receiving surface of test-body.
E' = absorptivity of charge.
H = heat transfer, C.H.U./sq. ft./hr.
H_c = heat transfer by convection.
H_R = heat transfer by radiation.
H_1, H_2 = heat transfer from two diametrically opposed hemispheres.
H' = net heat transfer to the charge.
m = mass of test-body, lb.
s = specific heat of unit mass.
T = temperature of test-body, °K. (°C. absolute).
T_R = mean radiant temperature of surroundings, °K.
T_{R_1}, T_{R_2} = mean radiant temperature of two diametrically opposed hemispheres, °K.
T' = temperature of charge, °K.
t = temperature of test-body, °C.
t_g = gas temperature, °C.
t' = temperature of charge, °C.

* Received October 2, 1945.

† For *Right Side* and *Right End* similar definitions apply.

τ = time, hr.
σ = Stefan's constant ($10 \cdot 1 \times 10^{-9}$ if H is in C.H.U./sq. ft./hr. and T is in °K.).
Ω = mean solid angle subtended at the receiving surface by the hot surface.
$dT/d\tau$ = rate of rise of temperature, °C./hr.

I.—Introduction.

It was formerly common practice to assess the performance of a furnace entirely in terms of its maximum possible output of serviceable fired material. More recently, however, the tendency has been to regard the thermal efficiency (or quantity of fuel consumed per unit of output) as an equally important criterion. The thermal efficiency of a furnace depends almost entirely upon two factors: (*a*) The fraction of the heat released by combustion which is lost by radiation through openings and by conduction through brickwork, and (*b*) the fraction of heat released by combustion which passes out of the heat-utilizing region as sensible heat in the products of combustion.

As regards (*a*), the output and thermal efficiency go hand-in-hand, since an increase in the amount of material treated does not raise appreciably the actual heat losses from the furnace, and hence the heat loss per unit of material is thereby reduced. On the other hand, (*b*) increases with output because the greater the heat transfer required the greater must be the temperature difference between the gases and the charge. This is particularly important in high-temperature furnaces, where the flame temperature is not very much higher than the furnace temperature. Now if it were possible to increase the coefficient of heat transfer, the same amount of heat could be pumped into the charge with a smaller temperature difference. This coefficient is, therefore, of the highest importance from the point of view of obtaining a good overall efficiency.

Heat is transferred from the flame to the charge by radiation and convection. The heat-transfer coefficient thus corresponds to the sum of two effects. Improvements in the radiation heat-transfer with a given temperature-difference between the flame and the charge can only be obtained by increasing the emissivity of the flame, since the furnace designer cannot control the adsorptivity of the charge. Improvements in convection can be effected by increasing the velocity at which the gases impinge on the charge.

Convection is therefore largely limited by the erosion resistance of those refractories which serve to maintain the requisite velocities. Hence the greatest improvement in furnace firing will probably arise from the discovery of new methods of increasing flame radiation.

The development of an instrument for measuring flame radiation is the first step towards the investigation of methods for increasing it. Such an instrument would enable an assessment to be made of the effects on the radiating power of the flame of: (*a*) The water vapour and carbon dioxide content, (*b*) delayed combustion (which gives rise to soot formation), and (*c*) the addition of hydrocarbons. It is virtually impossible to predict the effect of these factors with any accuracy by calculation, both because of the large number of variables and because many simplifying assumptions have to be made before mathematical calculation is possible. On the other hand, it appears probable that interesting effects would be observed if a furnace were operated so that only one variable at a time was changed, provided that an experimental technique were available for direct measurement of the heat-transfer coefficients.

Now the process of heat transfer by radiation is essentially dynamic, *i.e.*, even when two bodies are at the same temperature they will exchange heat at a rapid rate. Consequently, when two radiators, such as the furnace flame and the charge, are at different temperatures a single measurement of the net heat flowing from one to the other does not tell the whole story. Thus a certain net radiation may correspond to a charge at 1400° C. and a flame at 1600° C., to a charge at 1600° C. and a flame at 1750° C., or to a more highly reflecting charge at 1400° C. and a flame at 1750° C. For this reason it is useful to measure the heat flowing upwards by radiation from the charge and that flowing downwards to the charge separately and to obtain the difference by subtraction. A further advantage of an instrument which can read the upward and downward radiations separately is that it can be used also between the crown and the flame so as to give the total heat radiated back into the furnace by the crown as well as the net heat flowing into the crown.

The heat transfer over the hearth area of a furnace should vary as little as possible, and an instrument exploring this variation would be invaluable in designing a furnace so as to make the best use of the available heat. In particular, if it could be used in conjunction with a furnace in which all the steelmaking variables were kept constant, the effect of variations of heating power upon output could readily be found.

These and similar considerations led the authors to the conclusion that they could render considerable service to the furnace-building and furnace-using industries by developing a suitable heat-flow meter. Since, as has been indicated, radiation is of greater importance than convection in high-temperature furnaces, it was decided to concentrate first on an instrument which would indicate the radiation upwards and downwards without taking account of effects due to convection. Although these effects may be an appreciable

fraction of the transfer they are unlikely to upset any broad conclusions drawn from the work.

The value of the heat-flow meter has been recognized by a number of earlier workers in this field. The instruments used and the results are described in the next section.

II.—Measurement of Heat Flow in Furnaces: A Survey of Earlier Work.

What was probably the first attempt to devise an industrial heat-flow meter was made in 1927 by the Russian scientist Kirpitchev. All that is known of his work has been derived from a later Russian paper. He apparently used a "cylindrical thermal probe" and did most of his work in boiler furnaces. His instrument took no account of the direction of heat flow.

In 1932 Häse [1] constructed an instrument (Fig. 1) consisting of a copper sphere, 8 cm. in dia.,

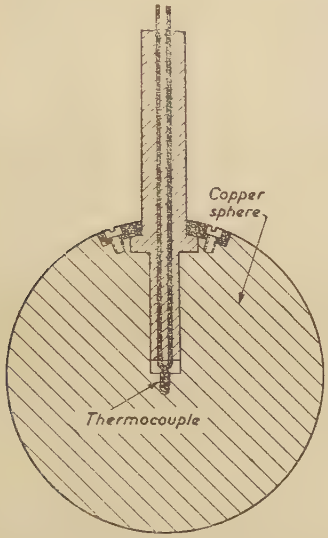


Fig. 1.—Häse's Heat-Flow Meter.[1]

with a thermocouple located at the centre. By means of a movable arm this sphere could be placed in any desired part of the furnace. The procedure was to measure the time taken for the temperature at the centre of the sphere to rise from 300° to 400° C.

Häse found experimentally that the total heat required to raise the temperature of the sphere over this range was approximately independent of the rate of heat input to the sphere. Hence the heat transfer Q is given by a formula of the type $Q = 81{,}000/t$ kg. cal./hr., where t is the time taken for the temperature of the centre of the sphere to rise from 300° to 400° C.

By measuring the difference in visibility of polished and blackened surfaces, Stoffregen [2] attempted to ascertain the degree to which a furnace could be regarded as a black body. Although the furnace had a large temperature gradient along its whole length, it was shown that each cross-section could be taken as a black body without producing great error, provided that no body in the vicinity was heated by the gas to a temperature much greater than that of the walls. Stoffregen also used Häse's total heat-flow meter to examine the variation of heat transfer across the width of the furnace.

Croft and Schmarje [3] described a "steady-state" heat-flow meter in 1935. It consisted essentially of a calorimeter (Fig. 2), cylindrical in form and 1·6 in. in dia., with a fused quartz window. Water, at a rate of flow of 30–35 lb./hr., was used both to cool the calorimeter and to serve as the calorimetric fluid. The rise in temperature of the water was measured by means of a copper–Constantan thermocouple. The calorimeter was surrounded by two independent water-cooled chambers and separated from them by the air

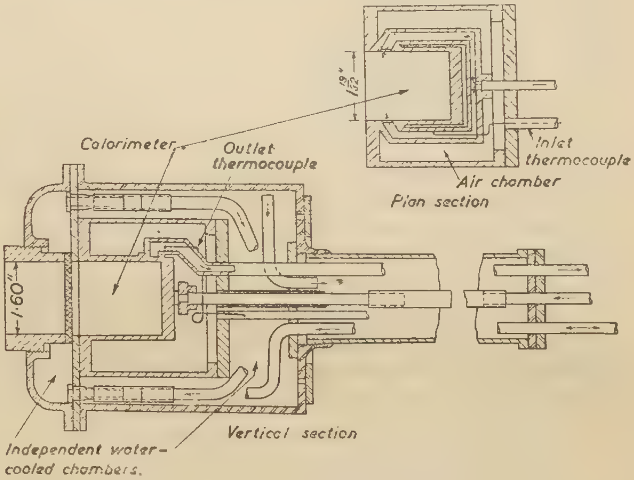


Fig. 2.—First Heat-Flow Meter of Croft and Schmarje.[3]

space. The instrument was calibrated by comparison with a true black-body absorber. With this instrument Croft and Schmarje were able to show that the Hudson-Orrok [4] formula was applicable to a furnace in which a considerable proportion of the water-cooled surfaces were slag-covered, and that the Wohlenberg [5] formula was correct for clean surfaces. They also derived a tentative formula taking into account the dirtiness of the surface.

In the following year (1936), Croft and Schmarje published an addendum to their previous paper, in which they described a means for separating the heat transfer by radiation from that due to convection [6] (Fig. 3). They minimized the effect of the latter by surrounding the calorimeter with a screen of high-velocity air. This enabled them to modify their original tentative equation and also to derive a formula for deducing the convection and radiation transfers separately.

In 1936, Hottel, Meyer, and Stewart [7] discussed the significance of temperature measurements in industrial furnaces. They also described a "thermometric" heat-flow meter (Fig. 4). This consisted of a pair of thermocouples attached to thin metal discs, mounted on either side of, and flush with, the surface of a slab of kaolin brick.

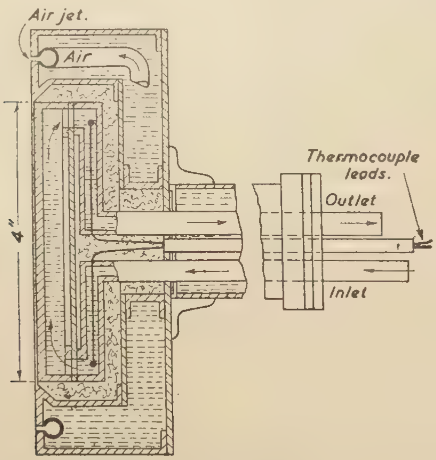


FIG. 3.—Second Heat-Flow Meter of Croft and Schmarje.[6]

The instrument was calibrated in front of a vertical hotplate. The principle of the instrument is that if the metal plates are thermally black, when equilibrium is reached they radiate as much heat to their surroundings as they receive, and hence the intensity of radiation is proportional to the fourth power of the absolute temperature of the discs as measured by the thermocouples.

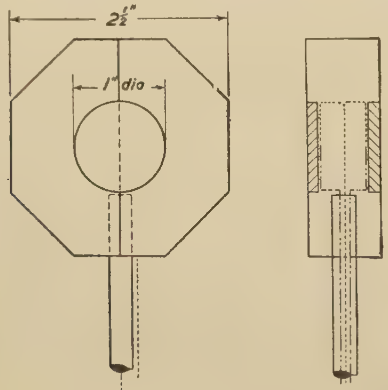


FIG. 4.—Hottel, Meyer, and Stewart's Heat-Flow Meter.[7]

Styrikowitsch [8] described two heat-flow meters which were employed in boiler furnaces. The first (Fig. 5) was a steady-state instrument which consisted simply of a water-cooled calorimeter (A) supported by a water-cooled arm (B) from which it was thermally insulated. The rise in temperature of the water was measured by thermometers (C) placed in the water stream (D). It was found that an excessive time was required for taking readings with this instrument, and Styrikowitsch apparently made no use of it, except as a means of calibrating his second instrument (Fig. 6). This was similar in principle to that of Hottel, except that it was mounted on a water-cooled arm and the element facing the crown was given only a limited angle of vision. Since the instrument was calibrated, and the cooling

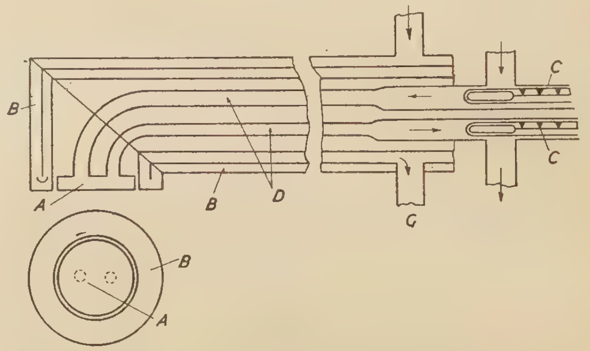


FIG. 5.—Styrikowitsch's First Heat-Flow Meter.[8]

conditions were maintained constant, the loss to the main arm did not affect the accuracy of the readings.

Styrikowitsch showed that instruments which focus radiation on to a thermocouple, such as Féry pyrometers or ardometers, provided that they have a fluorite optical system, can be used for measuring the intensity of flame radiation under various conditions but not the net heat transfer to a given surface in the furnace. He carried out a

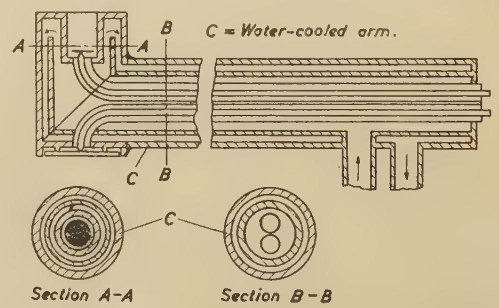


FIG. 6.—Styrikowitsch's Second Heat-Flow Meter.[8]

number of experiments to determine the distribution of radiation from flames in boiler furnaces, and produced a series of pictures illustrating this distribution in the plane of the water wall. Styrikowitsch found that the oil components of high molecular weight produced a large quantity of soot, and hence gave a blacker flame than is obtained when natural gas is burnt. The blacker oil-flame produces a sharper radiation-intensity gradient than the natural gas; the latter gives a very even intensity distribution.

The most recent paper in this field was published in 1939 by the Russian, Kazantsev.[9] He developed what he calls a "disc thermal probe" (Fig. 7), which consists of a cylinder of heat-resisting steel open at one end, within which is a core of electrolytic copper, the exposed surface of which is serrated and coated with uranium oxide to produce

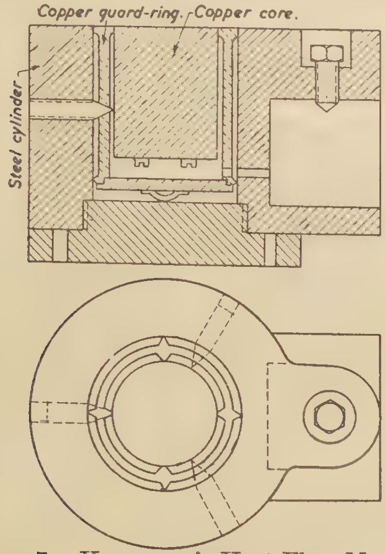


Fig. 7.—Kazantsev's Heat-Flow Meter.[9]

a thermally black surface. The height of this core depends on the furnace temperature; a core for use at 1600° C. is 40 mm. high, and at 1300° C. is only 20 mm. high. Between the core and the steel cylinder, and separated from them both by small air spaces, is a copper guard-ring to prevent heat leakage. The inter-radiation between the core, the ring, and the cylinder is minimized by nickel-plating all the necessary surfaces. In use, the procedure is to measure the time taken for the temperature of the copper–Constantan thermocouple, at the base of the block, to rise from 100° to 200° C. The instrument thus received only directed radiation.

With this instrument Kazantsev was able to study in detail the effect which the method and rate of charging has upon the melting time. He also measured the effect these factors have upon the intensity of the boil and the rate of heating-up the molten steel. He suggested that the output of an open-hearth furnace could be increased by removing the resistance to flow in the flues, by flame control, and by heat insulation. This, as far as is known, is the only record of the use of a heat-flow meter in an open-hearth furnace.

Particulars of the various types of heat-flow meters are collected at the foot of the page.

III.—Theoretical Basis of the Heat-Flow Meter.

General.

Two problems arise in the design and use of a heat-flow meter: (*a*) How to measure the amount of heat falling on the test-body when it is inserted to a specified point in a furnace, and (*b*) how to deduce from this value the total rate at which heat flows to the charge at that point. A problem of equal importance to the furnace designer is the calculation of the rate at which heat would flow to a body at any specified temperature if it were placed at that point.

The general law governing both the heat received by the charge and the heat received by the test-body is:

$$H = C(t_g - t) + \sigma E(T_E{}^4 - T^4)\text{C.H.U./sq. ft./hr.}^* \quad (1)$$

Calculation of the Heat Transfer to the Thermometric Type of Instrument.

In thermometric heat-flow meters what is actually measured is the temperature assumed by a body partially or wholly exposed to the heat. The heat received, H, is derived either from the final temperature taken up by the body or from the rate of rise of temperature.

The final temperature attained by the body is calculated by substituting $H = 0$ in equation (1);

Investigator.	*Type of Instrument.*	*Conditions of Use.*	*Max. Rate of Heat Absorption,* C.H.U./sq. ft./hr.	*Remarks.*
Kirpitchev	Thermometric	Boiler furnaces	...	...
Häse	Spherical ball (no account taken of direction), thermometric.	...	...	Fig. 1.
Croft and Schmarje	Thermometric.	Used in wall of, and between tubes of, boiler furnaces.	31,700	Separated radiation from convection by means of an air jet (Figs. 2 and 3).
Hottel and others	Thermometric, with two opposing elements.	...	10,000	Time per reading was excessive (Fig. 4).
Styrikowitsch	Calorimetric and thermometric.	Boiler furnaces.	103,000	Time per reading: 10 min. with calorimetric type, 1 min. with thermometric type (Figs. 5 and 6).
Kazantsev	Thermometric, directional.	Open-hearth furnaces.	138,000	Fig. 7.

* σ = Stefan's constant ($10{\cdot}1 \times 10^{-9}$, if T is in °K.). Unless otherwise stated the test-body is assumed to have an emissivity of unity, *i.e.*, it is a perfect absorber.

then t and T are the temperatures of the body in °C. and °K. respectively. If the convection heat-transfer is small, or if $T_g = T_R$, then the temperature of the body is equal to T_R, the mean radiant temperature of the surroundings to which it is exposed.

In Hottel's instrument, T_R is the mean radiant temperature of the hemisphere of the furnace facing each disc. Hence, provided that convection is negligible, the net heat transfer to any other body is :

$$H = \sigma E(T_R{}^4 - T^4)$$

where T_R is the final temperature attained by the disc in °K.

Similarly, the net heat transfer by radiation through any small area in the furnace is given by :

$$H' = \sigma(T_{R_1}{}^4 - T_{R_2}{}^4)$$

where T_{R_1} and T_{R_2} are the two temperatures attained when using the disc facing in opposite directions on each side of the area.

In the instrument of Styrikowitsch shown in Fig. 6, on the other hand, the mean radiant temperature of the surroundings includes the temperature of the water-cooled surface behind the measuring disc; consequently the mean radiant temperature of the hemisphere of furnace can only be deduced from that of the disc by calibration.

In cases where the heat transfer is deduced from the rate of the rise of temperature of the body, the general formula is :

$$H = \frac{m.s.}{A}\frac{dt}{d\tau} \quad . \quad . \quad . \quad . \quad . \quad (2)$$

If the body is such that it can be assumed to have a uniform temperature throughout, under the actual heating conditions, then H can be calculated from equation (2). The values of m, s, and A can be obtained by direct measurement. This assumption cannot be made in the case of the Häse or Kasantsev instruments, and calibration is essential to give the heat transfer in terms of the rate of rise in temperature.

Calculation of Heat Transfer to the Calorimetric Type of Instrument.

Instruments of this type rely on the absorption of the heat falling on a given area by a suitable, measured flow of fluid. The actual heat transfer to the surface is derived from :

$$H = \frac{m}{\tau}.\frac{s}{A}(t_1 - t_2) \quad . \quad . \quad . \quad . \quad (3)$$

where m/τ = mass of fluid flowing per unit time, in lb./hr., and $t_1 - t_2$ = rise in temperature in °C. of the flowing fluid after steady conditions have been attained.

Where the receiving area A of the calorimeter is precisely defined, as in the Croft and Schmarje instrument of Fig. 3, no calibration is necessary as the heat flow to the calorimeter can be calculated with good absolute accuracy from equation (3). Where the angular aperture to which the area is exposed is uncertain, as in the Croft and Schmarje instrument of Fig. 2, the instrument must be calibrated to give H in terms of m/τ and $(t_1 - t_2)$.

Geometrical Considerations in Design of Receiving Element.

Where the heat-receiving element is situated at the end of a cavity which is separately cooled, the receiving surface is no longer exposed to the radiation from a complete hemisphere of the furnace. (It is assumed that the remainder of the hemisphere to which it is exposed is cooled to the same temperature as the receiving element.) Hence the measured heat transfer will depend not only on the mean radiant temperature of the part of the furnace to which it is exposed but also on the solid angle subtended at the receiving surface by this part of the furnace. For example, where the hot surfaces are at a uniform temperature of t °C. (T °K.), the heat transfer is given by :

$$H = \frac{\Omega\sigma}{\pi}(T_R{}^4 - T^4). \quad . \quad . \quad . \quad (4)$$

This formula is based on the assumption that the remainder of the hemisphere $(2\pi - \Omega)$ is cooled to the same temperature as the receiving element, assumed to be in the form of a small cone around the normal to the surface.

As far as geometrical factors are concerned, instruments in which each part of the receiving element can receive radiation from a whole hemisphere differ only in that some (such as Häse's instrument) have a convex receiving surface, so that the heat transfer is the average radiation from all sides, while in others the receiving surface is flat and receives radiation from one hemisphere only. Of these two types, only the second can be used for measuring the net radiation transfer through a plane. This is done by taking two readings with each part of the receiving element facing in opposite directions and subtracting one from the other.

Instruments so constructed that a small angle is subtended by the hot surfaces at the receiving element have the advantage that it is possible, by replacing the latter by a water-cooled target, to separate the radiation of a flame from that of the brick wall behind it.

Instruments of the flush type (*i.e.*, where the receiving element "sees" a solid angle of 2π) also receive full convection according to equation (1), whereas the recessed type with a small angle of "sight" receive only the radiation given by equation (4).

Calculation of Net Heat Transfer to the Charge from a Single Heat-Flow-Meter Reading.

It has been shown that the heat-flow meter gives either (*a*) the total heat transfer to the calorimeter due to convection and radiation :

$$H_c + H_R = C(t_g - t) + \sigma(T_R^4 - T^4)$$

where t and T are the temperatures of the sensitive element in °C. and °K., or (*b*) the heat flow due to radiation only :

$$H_R = \sigma(T_R^4 - T^4)$$

from which, since σ is known, H_R can be calculated from H as given by equation (4).

In general, it is not possible to calculate H' (the net heat transfer to the charge) from a single reading of either $(H_c + H_R)$ or H_R. The only cases where H' can be calculated from a single reading are the following :

(i) *Convection Negligible Compared with Radiation.*—In this case

$$H \simeq H_R \simeq H_c + H_R$$

and

$$H' = \sigma E'(T_R^4 - T'^4)$$
$$= E'(H_R + \sigma T^4 - \sigma T'^4) \quad . \quad . \quad (5)$$

T^4 is negligible for water-cooled elements, but in any case it can be calculated since T will be known; similarly we can, in general, assume that E' and T' are known, and H' can be calculated from the heat transfer to the instrument.

In this case it is also possible to obtain the net heat transfer through a small plane surface by radiation. The instrument is placed at the centre of the surface and readings of H (*viz.*, H_1 and H_2) are made with its surface in the plane facing, first, in one direction, and then in the opposite direction. Then the net heat transfer through the plane is given by :

$$H = H_1 - H_2 \quad . \quad . \quad . \quad . \quad (6)$$

(ii) *Flat Receiving Element.* H *measured when the surface temperature of the calorimeter is equal to that of the charge, and their emissivities are equal.*—Here $H' = H$; in practice such conditions can be met only by using a selected portion of the charge as a heat-flow meter, *e.g.*, by inserting thermocouples into a block of steel near the surface.

In all other cases a single reading of a heat-flow meter will not enable the heat transfer to be calculated with any degree of accuracy, and the use of the instrument will be confined to the measurement of the relative values of different flames and to relative distribution of heat transfer over the surface of the charge. The experimental work discussed later in this paper has been of the latter type. It is not improbable that, in the open-hearth and glass-tank furnaces in which the experiments were carried out, the convection heat transfer is small compared with the radiation and that the net heat transfer to the charge can be calculated with reasonable accuracy. Until this hypothesis has been confirmed, however, the readings must be regarded as having only relative significance.

Calculation of Net Heat Transfer to the Charge from a Pair of Readings.

Where two readings (into which the heat transfers by radiation and by convection enter in different known proportions) can be made, it is possible to calculate H and H_c separately. In this case, since the variation of H and H_c with the temperature of the receiving surface is known, the combined net heat transfer $(H + H_c)$ to the charge at any temperature T by radiation and convection can be calculated.

The net heat transfer by convection is :

$$H_c' = C(t_g - t') = H_c + C(t - t')$$

since

$$H_c = C(t_g - t).$$

C can be deduced either from $C = H_c/(t_g - t)$ or from the convection formulæ of Fishenden and Saunders.[10] Likewise,

$$H_R = \sigma E'(T_R^4 - T_c'^4) = E'(H_R - \sigma T_s^4 - T'^4)$$

as in equation (5).

The following four ways have been proposed for obtaining two readings into which convection and radiation enter in different amounts :

(1) The use of two sensitive bodies equally exposed to convection but having different known emissivities. This method has been found to involve the basic difficulty that the only type of surface which will remain at constant emissivity when exposed to the furnace gases is a deeply grooved black surface (emissivity nearly unity).

(2) The use of two sensitive elements with different surface temperatures. This method could, in theory, be applied by interposing a known thickness of refractory between the radiation and one calorimeter, but in practice it offers great difficulties owing to the action of the furnace atmosphere on the thin refractory coating.

(3) The use of a jet of air [6] (or, where combustible gas is present, of nitrogen) controlled from outside the furnace and arranged so as to sweep the hot gases from the surface of the calorimeter. The reading without the air-jet gives the sum of the radiation and convection heat transfer to the sensitive element. With the air-jet preventing convection, the reading is due entirely to radiation. This method has the advantage that the two readings are taken under conditions which are in every way comparable; it is, however, only applicable where the surface temperature and the air temperature do not differ greatly.

(4) It is possible to use a narrow-angle instrument (which measures radiation only) in con-

junction with a wide-angle type (giving radiation and convection). But this has the disadvantages that any error in calibration of the narrow-angle instrument will appear as a relatively large error in the convection and that the radiation values measured by the two instruments will be different unless the mean radiant temperature over the whole hemisphere to which one is exposed is equal to the radiant temperature of the small angle to which the other is exposed.

For completeness, one other point must be mentioned, namely, the possibility of surface-catalysed combustion or unloading of abnormal energy upon the receiving surface. According to Lewis and von Elbe [11] this is unlikely to occur under the conditions of normal flames even upon a hot thermocouple wire and hence even less upon a water-cooled surface. Nevertheless, it is a possibility which cannot altogether be ignored except by the comparison of heat-flow-meter readings with the measurement of the heat flow to an actual surface of the charge. This is another reason why the readings must be used for the assessment of the relative properties of different flames at different points rather than for the absolute measurement of heat transfer to the charge.

In this section we have discussed the means whereby a heat-flow meter can fulfil its function of measuring the heat flow at any point in a furnace system under actual working conditions. It should be emphasized that no attempt is being made to use such instruments for measuring flame emissivities.

IV.—Selection of the Type of Instrument to be Used for the Investigation.

The choice of the type of instrument to be used depends mainly on the objective set for the work. The aim in this case was to produce a research tool whereby trained investigators could study the processes taking place in the furnace and so obtain information which might lead eventually to improvements in furnace design. Hence it was decided to make an instrument which would be accurate rather than foolproof, and which could be operated continuously in the furnace for long periods at a time. Had the aim been to develop a commercial flame-radiation meter for routine use, quite a different type of instrument would have been selected for investigation.

When the problem of measuring heat flow in furnaces was first considered by one of the authors (M.W.T.) an instrument was envisaged which would require no thermocouple wires or other connections through the insertion door. This instrument was to consist of a metal disc placed over a hole in a brick; the combination when cool would be placed in the furnace, and the time required for the disc to melt and run into the hole would be measured by watching it from outside.

When the objective had been more clearly formulated, however, it was obvious that what was needed was a more elaborate instrument which could be used repeatedly and rapidly to give a large number of readings. For this reason the calorimetric type of instrument was chosen in preference to the thermometric type; a calorimeter, if made of thin sheet metal and with a rapid water-flow, can take up its final reading very quickly. In order to obtain the full benefit of this quick response and to avoid errors due to heat loss it was decided to use differential thermocouples with the junctions situated at the inlet and outlet of the calorimeter.

To enable this calorimeter to be inserted to any point in the furnace, it was decided to mount it at the extreme end of a plain cylindrical arm with the receiving face flush with the tube surface. There appeared to be a choice between two alternative designs for the supporting arm. Schofield and Grace [12] have shown that a plain steel tube encased in insulating brick can be used for a short time in an open-hearth furnace, but this method was rejected because the tube would itself soon heat up and cause appreciable heat transfer to the calorimeter embedded in it. The alternative of using a water-cooled arm was therefore adopted, in spite of the fact that it would require an appreciable quantity of water. Such an arm also has the advantage of cooling instantly on removal from the furnace, and is thus easy to handle.

The use of a water-cooled arm also made possible the addition of an air-jet for separating radiation and convection, and, for reasons discussed in the preceding section, this method was chosen, although it has not yet been fully worked out. This air-jet could either be arranged to flow at right angles to the calorimeter surface (preventing the gases from reaching the calorimeter by forming a barrier) or it could be made to sweep closely over the calorimeter surface. Of these two methods the former was chosen because it required no projecting guide-lip.

V.—Design Problems and their Solution.

A few details will now be given of the practical difficulties met with in the course of the development work on the heat-flow meter.

Supporting Arm.

The first experiments were designed to ascertain whether it was possible to make a water-cooled probe which could be continuously maintained in the flame of a high-temperature furnace. The first probe, model O, consisted simply of three concentric tubes about 10 ft. long. The outer tube was made of 16-gauge solid-drawn steel, 2 in. in

outside dia. This was the size proposed for the heat-flow meter and was chosen as being the tube of smallest diameter having sufficient rigidity. It was so constructed that water introduced into the inner annulus would flow down to the extreme end and back along the outer annulus. The inner tube was left open and could be used for taking gas samples.

It was not then known what requirements the design of water-cooled probes for this purpose must satisfy, and as this first probe proved quite successful the nature of these requirements was not revealed by the experiments. The results of the experiments made with this probe encouraged the authors to design and build a second instrument (model I.) complete with calorimeter. This instrument was constructed of a number of short lengths of tube with overlapping joints, which were found to cause local overheating. It was therefore clear that in designing this type of instrument care must be taken to ensure that every part is in intimate contact with actual flowing water.

Another weakness of this type of design became evident when tests were carried out on the next probe to be constructed (model II.). This had precisely the same tube sizes as the previous design, but the outer tube was in one continuous length. It was clear from the first trial of this instrument that it failed to satisfy another essential condition which had been fulfilled by chance in the original probe, model O. When model II. was inserted in the furnace a hot-spot formed on the upper surface of the tube, causing the whole arm to bend. It was clear that this trouble was due to the formation of a pocket of either steam or air.

The difficulty was overcome in the next instrument (model III.) by reducing the cross-sectional area of the outer annulus. The object of this was to create a high water-velocity, thus scouring the surface and sweeping away any steam or air bubbles as they formed.

This instrument withstood a 10-hr. period of use in a glass furnace, but eventually all the welds around the calorimeter end of the instrument gave way, owing to the force set up by the differential expansion of the outer tube compared with that of the inner one to which it was fixed at both ends. The next instrument (model IV.) was therefore fitted with expansion bellows. This met all the requirements regarding the main supporting arm satisfactorily.

To summarize, the essential points in the design of the supporting arm are: (1) A sufficient water velocity to ensure that all surfaces exposed to the heat of the furnace are kept thoroughly scoured (5·0 ft./sec. for glass furnaces and 10 ft./sec. for steel furnaces); (2) the avoidance of projecting pieces of metal, even though they may be contiguous to a well-cooled part of the instrument; (3) actual contact of the whole of the outer tube with flowing water (*i.e.*, no overlapping joints); (4) care to ensure that there are no corners in which the water velocity is liable to be low or in which air or steam can collect; and (5) means to prevent the stress set up by differential expansion being borne by the welds.

Calorimeter.

A high water-velocity was found to be essential also in the calorimeter. In the first calorimeter, this requirement was not satisfied and steam was produced, causing violent fluctuations in the water rate and making it impossible to obtain a satisfactory reading. The reduction of the cross-sectional area and consequent increase of the water velocity overcame this difficulty.

The first calorimeter design had one thermocouple junction in the inlet and one in the outlet; these were connected together differentially so that the e.m.f. across the two junctions gave the temperature-rise of the water passing through the calorimeter. At that time an accurate but slowly adjustable potentiometer was being employed, and, owing to the sensitivity of the galvanometer to vibration, quite an appreciable time was taken to get each reading. To reduce this time, a new calorimeter was fitted having four junctions in the inlet and four in the outlet, all differentially connected. Before the work in the steelworks was commenced, this instrument was replaced by a quick-reading potentiometer which obviated the need for the multiple thermocouples as it could give rapid and accurate readings on the e.m.f. of a single junction.

The essential points in the design of calorimeters for use in the heat-flow meter are: (1) Narrow water passages, giving a high water velocity; (2) hard-soldering of all joints, since any momentary fall of water-rate will cause the destruction of the calorimeter, and because the temperature gradient through the metal is high; and (3) surfaces serrated and blackened, to produce the maximum possible absorptivity.

Auxiliary Equipment.

In the earlier experiments the cooling water for the main arm was measured with an ordinary integrating-type meter, but later a Venturi coupled to a mercury differential gauge was substituted. This gave constant indication of the actual water rate, and it is anticipated that, should overheating occur, visible warning would be given by violent fluctuations of the mercury level. (The use of a differential meter has been found to give such warning in respect of the calorimeter.) As a further precaution, a mercury-in-steel dial thermometer has been installed in the outlet of the cooling arm. In operating the instrument more reliance is placed upon this outlet tempera-

ture, which under no circumstances is allowed to exceed 60° C., than upon the water rate.

It was found necessary, for the comfort of the operator, to attach a handle enabling him to stand at least 6 ft. away from the furnace. A special trolley to support the instrument has not so far been used.

Constructional Details.

The instruments used in the tests (to be described later in this paper) are referred to as models VI. and VII. They are almost identical and their design is shown in Fig. 8. Figs. 9(*a*) and 9(*b*) are photographs of the exterior. Referring to Fig. 8, the three solid-drawn steel tubes *A*, *B*, and *C* are arranged concentrically. Water is introduced into the inner annulus between tubes *B* and *C* *via* the inlet, whence it flows down the whole length of the instrument, back along the outer annulus between tubes *A* and *B*, and to waste through the outlet. At the end remote from the inlet and exit, a trough *F* is let into the supporting arm to hold the calorimeter *G*, the receiving surface of which bridges the top of the trough. The expansion bellows are denoted by *L*.

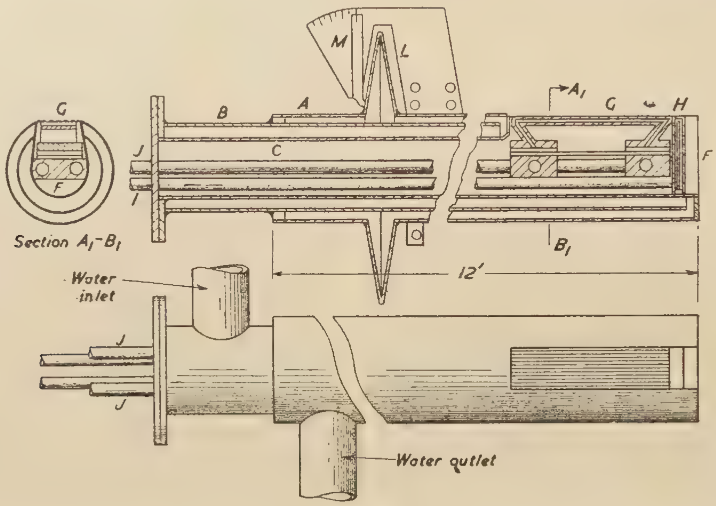


FIG. 8.—The Authors' Heat-Flow Meter.

The end of the calorimeter is shielded from radiation by means of a water-cooled plug *H*. The supply pipes *I* and *J* for the plug and the calorimeter, respectively, run along the full length of the instrument, within the innermost tube *C*. Fig. 9(*b*) shows how it is possible, by withdrawing the end plug with its supply tubes, to remove the calorimeter from the body of the supporting arm.

The difference between the two instruments lies in the construction of the calorimeter. That used in model VI. (Fig. 10(*a*)) consists of three parts: A short length of copper tube *A*, and the inlet *B* and outlet *C*. The copper tube, which is of 16-gauge, is pressed flat until the water-passage depth is $\frac{1}{16}$ in., and its upper face is serrated so as to approximate more closely to a black-body absorber. The inlet and outlet are hard-soldered on to the copper tube and are drilled and tapped so that they can be bolted on to the water-supply and waste pipes, this being where the thermocouples are located.

The calorimeter used on model VII. (Fig. 10(*b*)) consists of four pieces: A brass block *A*, in which narrow water passages are cut, the side-piece *D* and two end-pieces *B* and *C*, all of which are soldered on to the brass block. The exposed face is serrated as before. The thermocouples are insulated with a coating of shellac compound and

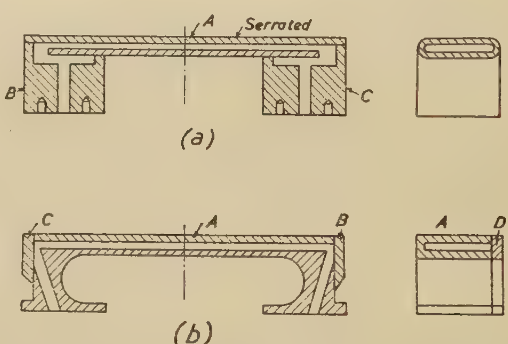


FIG. 10.—Construction of Calorimeter used in (*a*) Model VI., and (*b*) Model VII.

are clamped between two pieces of ungraphited sheet at the point where the calorimeter is attached to its supply tubes.

VI.—RESULTS OBTAINED AT THE CHARLTON WORKS OF THE UNITED GLASS BOTTLE MANUFACTURERS.

A full description of the furnace is given in Appendix II. The most important features of a glass-tank furnace are that it is a regenerative

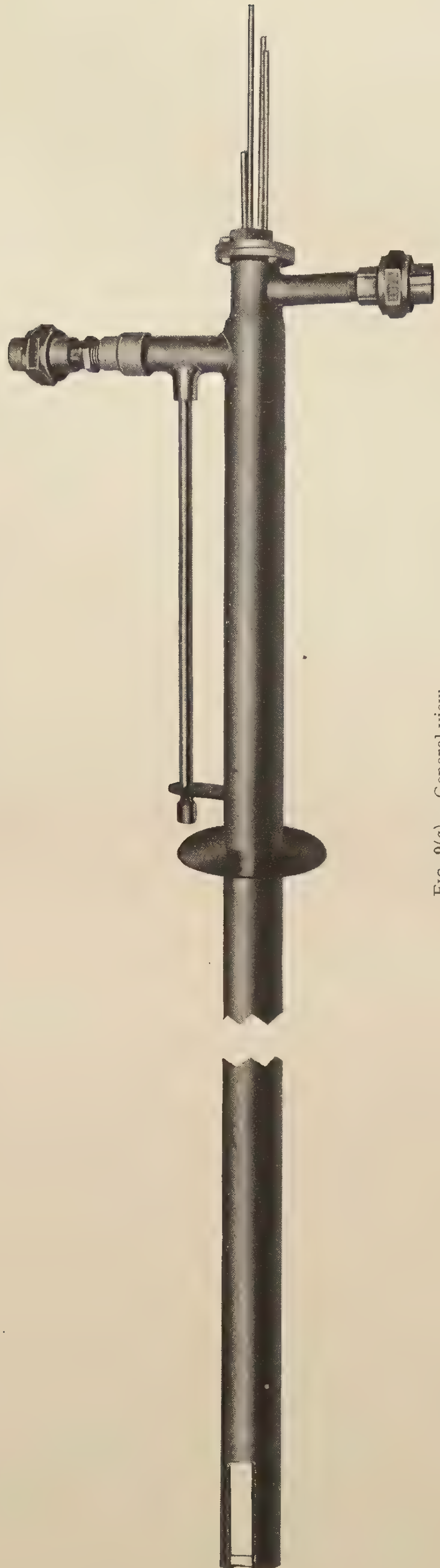


FIG. 9(a).—General view.

FIG. 9(b).—With Calorimeter and Plug withdrawn.

FIG. 9.—The Authors' Heat-Flow Meter, Model VI.

furnace, with the flame direction reversing every ½ hr.; it operates continuously (*i.e.*, without any time cycle except that of reversals), and it has three or four flames passing across a roughly rectangular chamber.

General Experimental Procedure.

A diagrammatic sketch of the furnace showing the position at which the instrument was inserted, is given in Fig. 11. Generally speaking, the

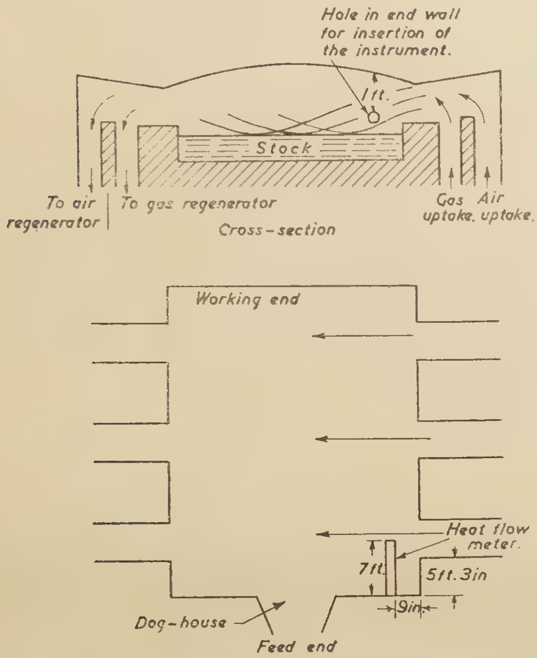


FIG. 11.—Glass Furnace, showing Position of Instrument.

instrument was inserted through a sight hole on one side of the "dog-house" to a distance of 7 ft. from the exterior of the furnace. This brought the calorimeter to a point on the centre line of the

as close as possible to the surface of the glass. It was not until work had commenced at a steelworks that a more reliable method was used. Careful watch had to be maintained on the positions of the batch piles, and the instrument occasionally had to be raised to allow them to float underneath. The batch, in the form of a heap of powdered raw materials required for making glass (sand, limestone, soda ash, &c.), is pushed in at the beginning of each ½-hr. reversal. Each pile then floats about on the surface of the previously melted glass until it is itself melted.

Variation with Time of Downward Heat Flow and Net Transfer to the Charge.

In these tests, the results of which are given in Figs. 12, 13, and 14, readings were taken throughout a number of cycles. In all cases the instrument was left in the furnace through the entire half-cycle and removed just before each reversal for cleaning and reblacking; it was re-inserted when the reversal was complete.

It will be noticed that the upward heat transfer from the stock varied considerably. In every case where the reradiation from the stock was very small it was noticed that the calorimeter was facing a pile of cool batch.

With two exceptions all these curves were obtained using producer-gas firing. The curves shown in Figs. 12 and 14 were obtained using creosote pitch; no change was made in procedure.

A summary of mean values of downward heat flow obtained in the glass-tank furnace is given in Table I.

Variation of Heat Transfer along the Length of the Flame.

The curves shown in Fig. 15 were obtained by inserting the instrument with the calorimeter

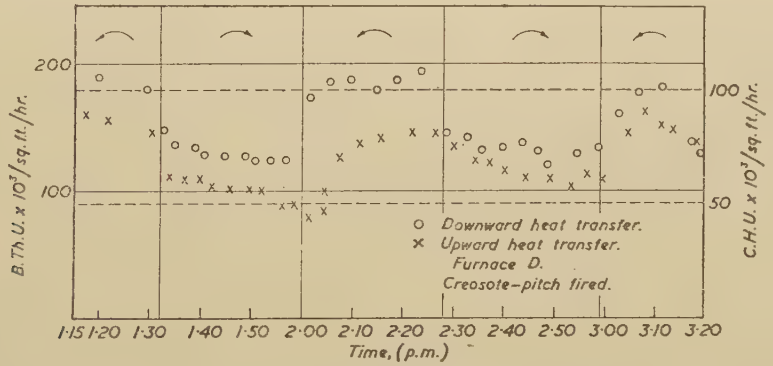


FIG. 12.—Upward and Downward Heat Transfer, showing that reradiation of the glass follows the downward heat flow.

first port. In order to eliminate convection or radiation from the flame, the reading of the upward heat transfer was taken by placing the calorimeter

facing upwards, *i.e.*, measuring the downward heat flow, and taking readings at various distances in, up to 7 ft. The instrument was inserted hori-

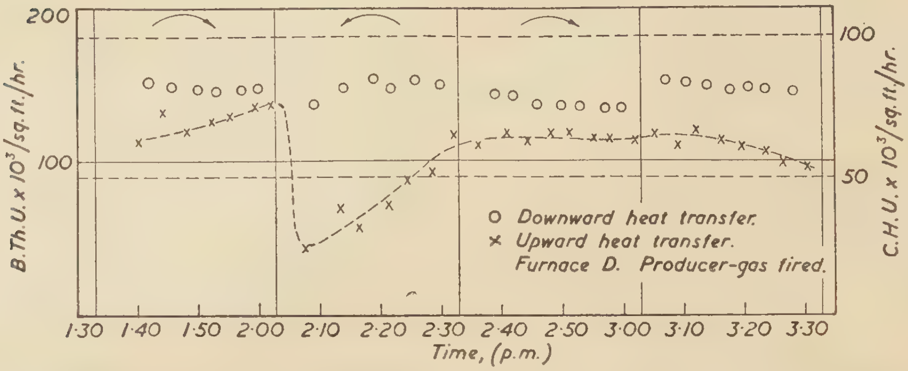


FIG. 13.—The Effect of Floating Cold Batch on the Upward Heat Flow in a Glass Furnace.

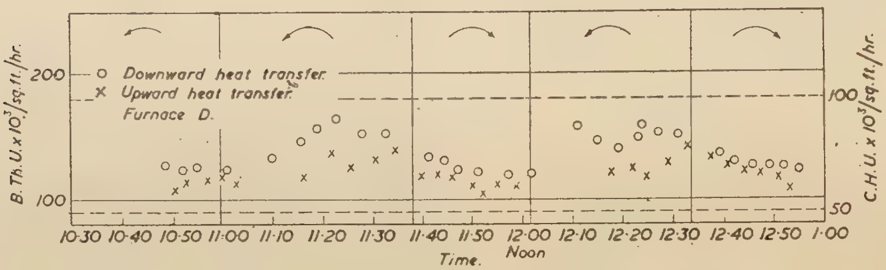


FIG. 14.—Variation with Time of the Net Heat Transfer to the Charge. Creosote-pitch fuel in a glass furnace.

zontally into the furnace, *i.e.*, with the calorimeter about 1 ft. above the surface of the stock and well enveloped by flame. The curves are given for the flames passing in either direction.

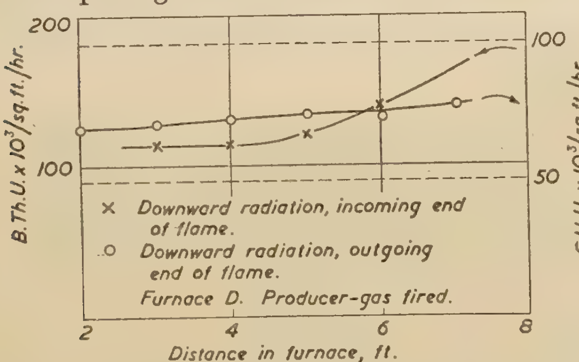


FIG. 15.—The Relative Width of the Flame at its Tip and Base, as shown by the downward heat flow.

Heat Transfer to the Crown.

The procedure adopted in this test was exactly the same as that described in connection with Fig. 12, except that the instrument was tilted so that the calorimeter was close to the crown. In this position the instrument was well above the flame. Occasional readings were taken at the surface of the stock as before. The results are shown in Fig. 16.

With the flame travelling from right to left and the instrument on the right-hand side of the furnace, the mean reading of downward heat flow was 116,000 C.H.U./sq. ft./hr., and the corresponding reading of upward heat flow was also 116,000 C.H.U./sq. ft./hr. After the reversal, with the flame travelling from left to right, the downward heat flow was 145,000 C.H.U./sq. ft./hr. and the upward heat flow 142,000 C.H.U./sq. ft./hr. The net heat transfer to the crown can

TABLE I.—*Summary of Mean Values Obtained in a Tank Furnace of the United Glass Bottle Manufacturers.*

Relative accuracy about ±3 units in last figure.

Date.	Fig. No.	Type of Fuel.	Incoming End of Flame, C.H.U. × 10³/sq. ft./hr.	Outgoing End of Flame, C.H.U. × 10³/sq. ft./hr.	Furnace Temp., °C.	Load, tons/24 hr.
4/8/43	12	Creosote pitch	101 ± 3·2	...	1450	53·4
19/11/43	15	Producer gas	91	78	1430	63·7
22/11/43	...	Producer gas	84·2 ± 1·0	78·4 ± 0·75	1455	59·2
26/11/43	13	Producer gas	83·4 ± 1·0	79·3 ± 1·3	1440	60·1
13/12/43	14	Creosote pitch	84·8 ± 2·5	72·8 ± 4·2	1420	52·2
15/12/43	16	Producer gas	89 ± 1·3	72 ± 1·1	1430	57·4

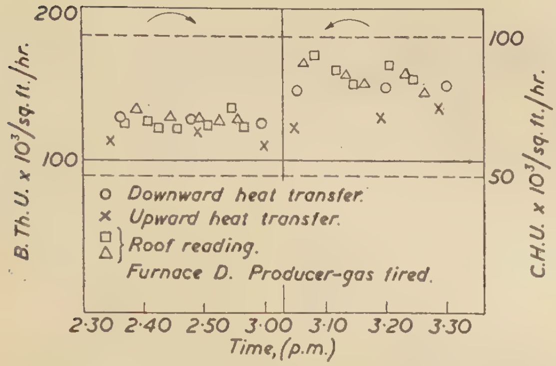


FIG. 16.—Net Heat Transfer to the Crown in a Glass Furnace.

therefore be regarded as negligible compared with the downward heat flow.

VII.—Results Obtained at the Steelworks of Messrs. John Summers & Sons, Ltd.

Details of the furnace construction are shown in Figs. 17(*a*) and 17(*b*) and a general description of the furnace operation is given in Appendix III.

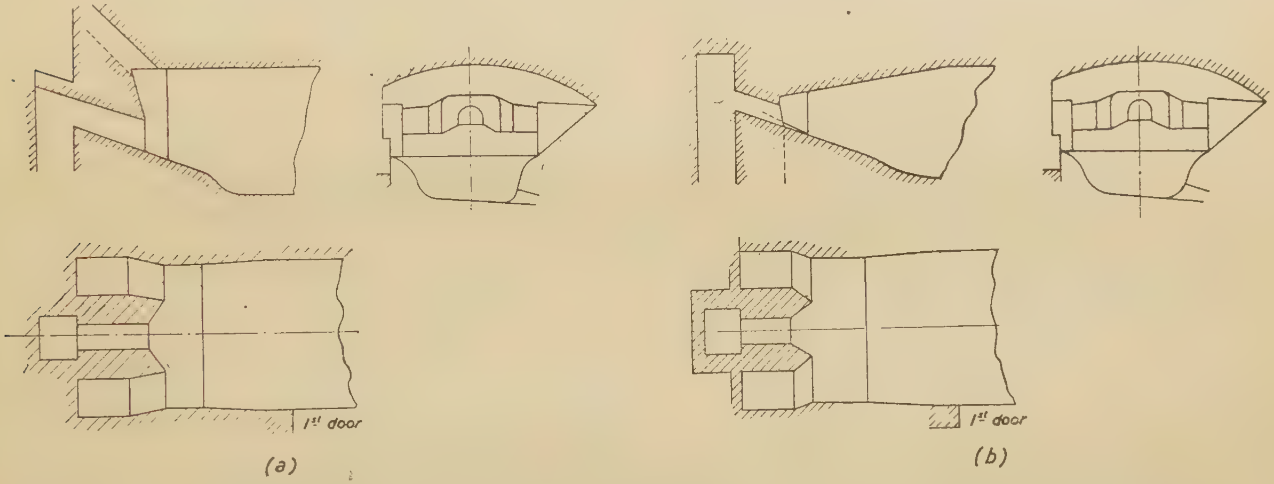


FIG. 17.—Port Construction (*a*) as now used on all furnaces, and (*b*) as used on furnace *R* up to July, 1944.

General Experimental Procedure.

The water supply for the instrument in the works was taken from a 900-lb./sq. in. main, and was throttled down to about 180 lb./sq. in. for use in the supporting arm. The supply to the calorimeter and end plug was taken from the same main. In tests near the steel surface the instrument was inserted through the lower sight-hole of the water-cooled furnace door, and for readings near the crown through the upper sight-hole. These holes are situated on the central axis of each of the three doors, at about 1 ft. and 4 ft. above the steel surface respectively.

In order to avoid any possibility of slag splashes falling on to the calorimeter during the measurement of the downward heat flow, the instrument was kept above the point at which the slag globules could be seen to fly. The readings taken with the calorimeter facing downwards continued to decrease until the calorimeter made contact with the slag surface. This point could be ascertained by noting the violent kick of the galvanometer as the calorimeter struck the surface. It was possible to keep the potentiometer balanced right up to the moment of entry into the slag. Hence the reading at a negligible distance above the slag surface could be ascertained. The slag and steel which adhered to the instrument could easily be dislodged.

After each pair of readings had been taken the instrument was removed from the furnace in order to clean the calorimeter. It appeared to be unnecessary to blacken the surface of the calorimeter, as blackening soon occurred within the furnace itself. All readings were taken on the longitudinal centre-line of the furnace.

Variation of Reading with Time.

One of the first tests to be carried out was to find the effect on the calorimeter of the building-up of deposits from the flame and charge. This was done by inserting the instrument into the furnace and taking readings approximately every ½ min. The effect of these deposits was in some cases appreciable, particularly in the second half-cycle. On subsequent tests it was overcome by cleaning the calorimeter between pairs of readings.

Variations of Downward Heat Transfer and Net Transfer to the Charge with Time.

Figs. 18–20 show readings taken throughout a series of cycles on two different furnaces. Only the downward heat flow is given in Figs. 18 and 19, as in these cases the technique for measuring the reradiation from the slag had not been worked out. Fig. 19 shows the variation of downward heat flow

over the last 5 hr. of a melt. Each of the points marked is the average of a number of readings in a half-cycle plotted against the time at which the half-cycle began. This melt was of rather longer duration than normal as the charge was a special one.

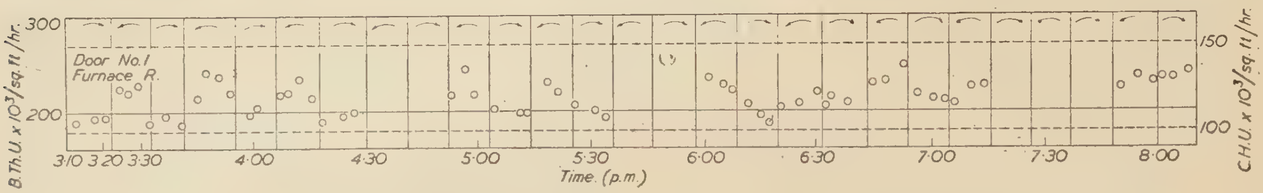


Fig. 18.—Downward Heat Flow under base of flame compared with that under the tip.

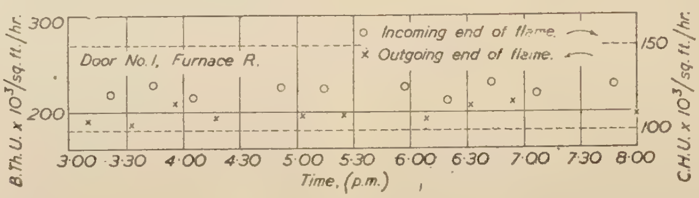


Fig. 19.—Variation of Downward Heat Flow with Time, showing that the downward heat flow remains sensibly constant during the refining period of 5 hr.

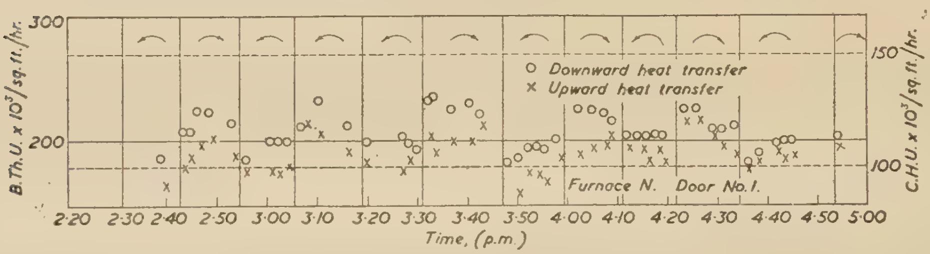


Fig. 20.—Variation of Net Heat Transfer over the last 2½ hr., showing that it falls off towards tapping time.

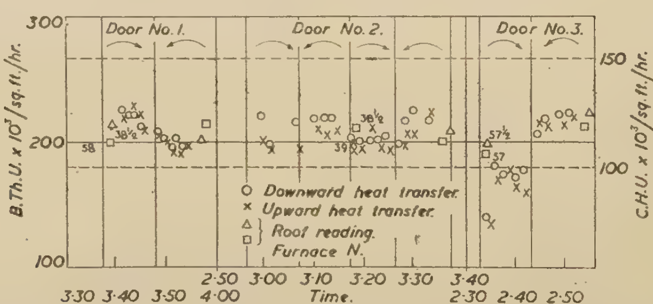


Fig. 21.—Downward and Upward Heat Flows at Different Distances along the Furnace.

Variation of Heat Flow and Net Heat Transfer along the Longitudinal Centre Line of the Furnace.

Fig. 21 shows a cycle test taken through each of the three furnace doors in turn. The procedure was to take readings throughout one complete cycle through one door and to repeat the process through the next door in the next half-cycle. A few readings taken close to the roof, with the instrument facing in both directions, are also given. These readings were often taken in a subsequent cycle, but are plotted in the equivalent cycle at the same door.

Variation of Downward Heat Flow across the Furnace.

Figs. 22 and 23 indicate the variation of downward heat flow as the instrument is inserted into the furnace at each of the three doors on two different furnaces.

It was not possible to measure the variation of the

net heat transfer to the bath across the width of the furnace because of the large angle at which the instrument would have had to be held in order to receive the reradiation from the slag at points near the door. All readings were accordingly taken with the instrument inserted into the furnace horizontally.

The readings near the crown were taken at

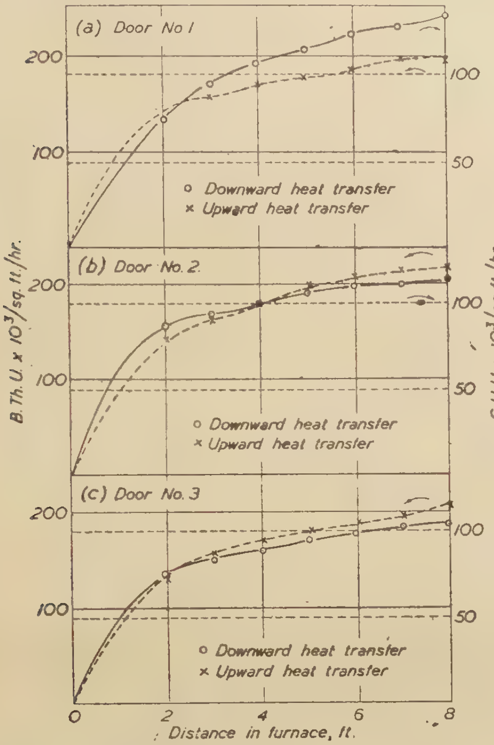


Fig. 22.—Distribution of Downward Heat Flow across Width of Flame (Furnace T).

the beginning and end of each half-cycle, and the reading of the net transfer to the charge at the centre line was also measured. These are shown graphically in Fig. 24.

An example of abnormally high downward heat flow is shown in Fig. 25, and readings showing the variation of downward heat transfer are presented in Table II.

Variation of Upward Heat Flow to the Calorimeter with Height above Steel Surface.

The instrument was inserted to the centre line of the furnace with the calorimeter facing downwards and the calorimeter was then raised high above the slag surface. The height of a point on the handle the same distance from the fulcrum as the calorimeter was measured and recorded. By raising this reference point the calorimeter was lowered through the same distance. Readings were taken for various heights and were plotted against the height of the calorimeter above the steel surface. The results are shown in Fig. 26.

The readings obtained after the point has been reached at which the calorimeter strikes the steel

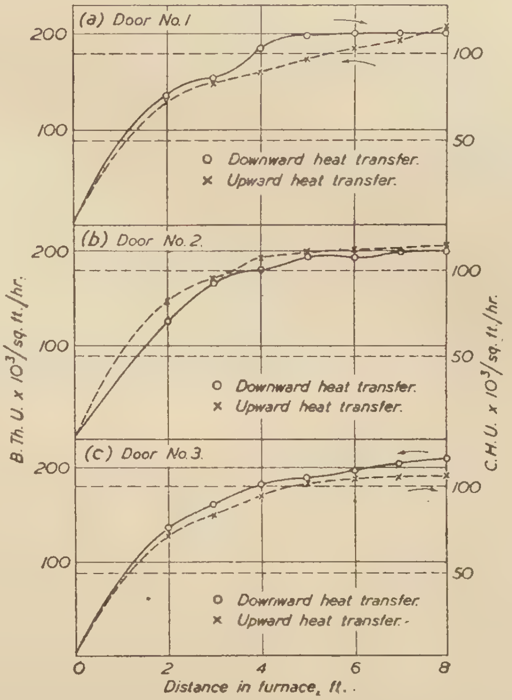


Fig. 23.—Increase of the Downward Heat Flow under Flame (Furnace S).

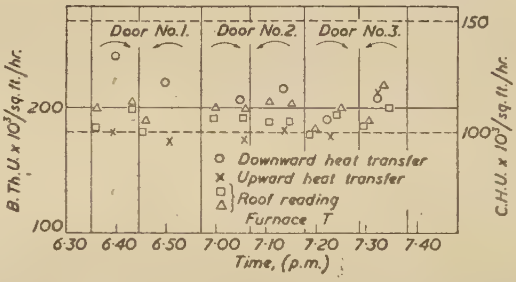


Fig. 24.—Net Heat Transfer to the Crown in a Steel Furnace.

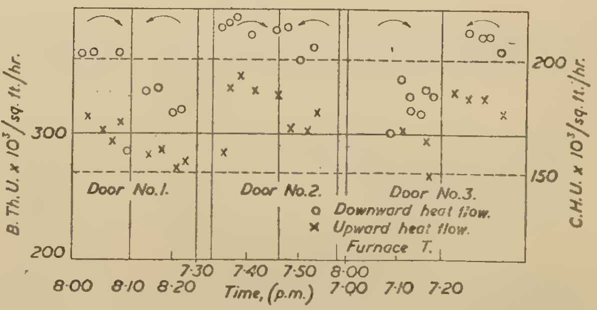


Fig. 25.—An Abnormally High Downward Heat Flow.

surface have no special significance. They were taken merely because the amount of contact with the steel surface could not be detected by the

TABLE II.—*Variation of Downward Heat Transfer on Each Test.* (C.H.U. × 10^3/sq. ft./hr.).

Date.	Fig. No.	Door No.	Furnaces at Messrs. John Summers & Sons, Ltd.									
			M.		*N.*		*R.*		*S.*		*T.*	
			L–R.	R–L.	L–R.	R–L.	L–R.	R–L.	L–R.	R–L.	L–R.	R–L.
25/5/44 *	...	3	183	208	...	...	...	...	...	...	...	...
6/6/44 †	...	3	...	...	...	...	...	159	...	...	...	...
20/6/44 ‡	...	3	...	...	...	...	102 ±3	125 ±2·0	...	...	...	...
21/6/44 ‡	18 and 19	1	...	...	...	...	130 ±2·4	115 ±1·7	...	...	...	...
15/8/44 †	...	2	...	...	107	110	...	...	...	...	...	...
16/8/44 †	...	1	...	...	...	...	...	...	...	...	207	190
16/8/44 †	...	2	...	...	...	...	...	...	...	...	214	208
16/8/44 †	...	3	...	...	...	...	...	...	...	...	179	211
5/9/44 †	21	1	...	...	121	111	...	...	...	...	...	...
5/9/44 †	21	2	...	...	112	119	...	...	...	...	...	...
5/9/44 †	21	3	...	...	96·1	124	...	...	...	...	...	...
6/9/44 †	...	3	...	...	...	...	...	...	...	...	105	117
17/10/44 *	22(*a*)	1	...	...	...	...	...	...	...	...	170	120
17/10/44 *	22(*b*)	2	...	...	...	...	...	...	...	...	125	140
17/10/44 *	22(*c*)	3	...	...	...	...	...	...	...	...	109	129
18/10/44 *	...	1	140	113	...	...	...	...	...	...	...	...
18/10/44 *	...	2	124	140	...	...	...	...	...	...	...	...
18/10/44 *	...	3	120	149	...	...	...	...	...	...	...	...
8/11/44 *	23(*a*)	1	...	...	...	...	...	...	124	130	...	...
8/11/44 *	23(*b*)	2	...	...	...	...	...	...	120	120	...	...
8/11/44 *	23(*c*)	3	...	...	...	...	...	...	112	131	...	...
28/11/44 ‡	20	1	...	...	121 ±2·0	109 ±1·7	...	...	...	...	...	...

* Single readings on central axis of furnace; readings taken at various distances across furnace.

† Single cycles on central axis of furnace; insufficient results obtained to permit calculation of standard error of the mean.

‡ The mean values in these tests are followed by twice the standard error of the mean. The tests were of downward heat transfer on one position on the central axis for not less than 2 hr.

normal method, as the test was carried out before the slag had properly formed.

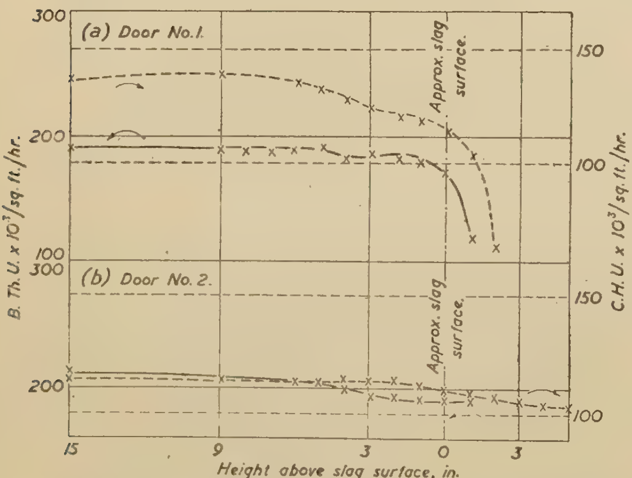


FIG. 26.—Variation of Upward Heat Transfer with Height above Slags, showing the importance of taking the upward heat flow close to the slag surface (Furnace *R*).

VIII.—RESULTS OBTAINED AT STEELWORKS OF MESSRS. SAMUEL FOX & CO., LTD.

An account of the furnace operation is given in Appendix III. and the design of port construction is shown in Fig. 27.§

Experimental Procedure.

The same procedure was adopted as in the tests described in section VII., except that the water supply was taken direct from the mains at approximately 125 lb./sq. in., giving a water flow of 1000 gal./hr. through the supporting arm. This was sufficient to keep the outlet temperature of the water below 60° C. when the calorimeter was at the centre line of the furnace. The water pressure at this works was not very steady and so a pressure regulator had to be incorporated in the calorimeter supply line.

It was found unnecessary to dip the calorimeter into the slag in order to obtain the upward heat flow at the slag surface, since there was no apparent variation of reading over the first 3 in. above the steel surface.

§ By permission of Messrs. Samuel Fox & Co., Ltd., and of Messrs. H. A. Brassert & Co., Ltd., designers of the furnace.

All the tests were conducted through a hole in No. 1 door, so that the calorimeter was about 7 ft. 6 in. away from the mouth of the port.

It was found that if the instrument was left in the furnace for more than about 3 min. the reading given by the calorimeter gradually decreased, owing to deposits of carbon and slag on the calorimeter surface.

Variation of Downward Heat Flow and Net Transfer to the Charge with Time.

Fig. 28 shows readings, taken throughout the last 2½ hr. of a melt, of both downward and upward heat flow at the bath surface. The value of downward heat flow at the incoming end of the flame varies between 115,000 C.H.U./sq. ft./hr. and 167,000 C.H.U./sq. ft./hr. The corresponding values for the outgoing end are 115,000 C.H.U./sq. ft./hr., and 150,000 C.H.U./sq. ft./hr. The values appear to vary widely throughout the test.

Variation of Downward Heat Flow across the Furnace.

The readings shown in Fig. 29 were taken in rapid succession as the instrument was inserted into the furnace. The test was repeated at three different heights above the slag surface. Since the upward heat transfer was taken at the same height above the slag surface as the downward heat transfer, the difference between the two readings is the net heat transfer flowing through a plane at that height, and not necessarily the net heat transfer to the charge.

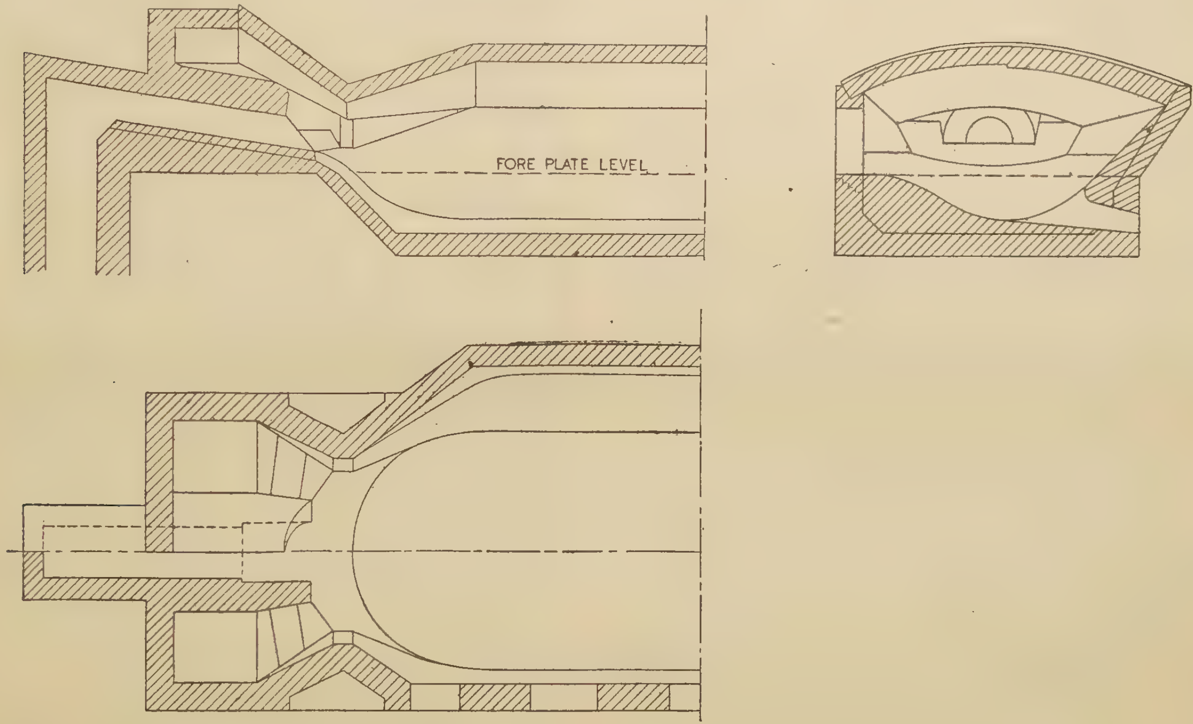


FIG. 27.—Port Construction as used in Furnace *K* (built to design of Messrs. H. A. Brassert & Co., Ltd.).

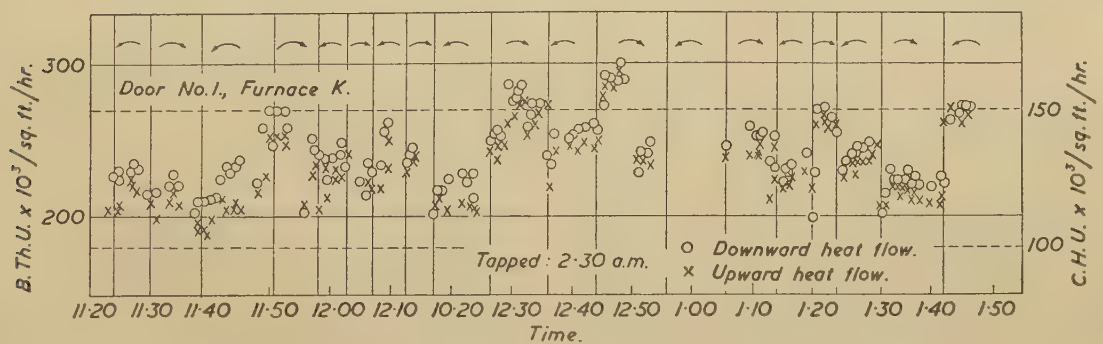


FIG. 28.—Random Variations of Downward and Upward Heat Flows with Time.

Variation of Upward and Downward Heat Flow with Height above the Slag Surface.

The procedure followed throughout these tests was similar to that given in section VII., except that the results are plotted against the actual

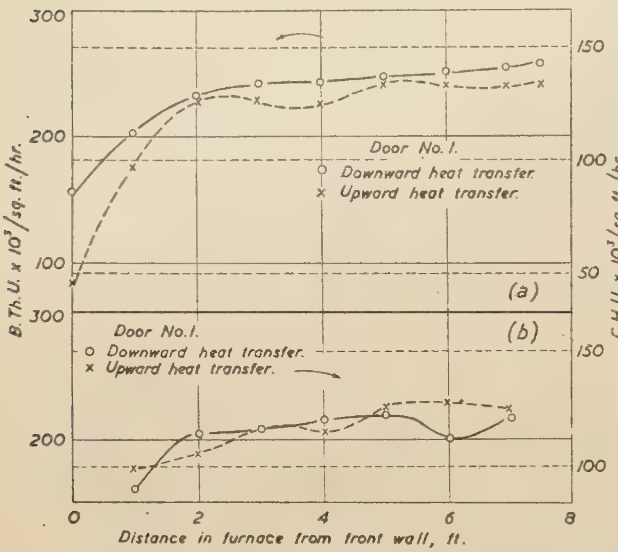


FIG. 29.—Distribution of Downward and Upward Heat Flows across the Width of the Flame. Flame travelling (*a*) right to left, (*b*) left to right. (Furnace *K*.)

height above the slag surface. These results are shown in Fig. 30.

IX.—CONCLUSIONS.

Design and Use of the Heat-Flow Meter.

The following conclusions have been drawn in connection with the design and use of a heat-flow meter:

(i) A water-cooled calorimeter supported by a water-cooled arm provides a practical method of measuring the heat flow in both glass-tank and open-hearth furnaces.

(ii) It is desirable to make the calorimeter detachable from the main arm; a convenient method of doing this without introducing errors due to end effects is to incorporate a separately cooled guard-ring or stopper to close the end of the arm.

(iii) It is essential that the outer annulus of the supporting arm should be made narrow enough to give a high water-velocity.

(iv) As a precaution against adventitious reductions of the pressure of the water supply, it is advisable to measure the main rate by means of a differential-type meter, so that a continuous visual indication is given of the actual water rate.

(v) It is advisable to operate the supporting arm in such a way that the outlet temperature of the water cooling it never exceeds 60° C., and to use a mercury-in-steel dial thermometer to measure this temperature. This gives the operator who is holding the instrument in the furnace an immediate warning indication of imminent danger. The operator at the control bench receives warning by observation of pulsations in the water-flow rate.

(vi) Even with a high water-velocity in the outer annulus, the temperature of the outer tube is considerably higher than the mean temperature of the water. Means must be provided to take up the resultant large expansion.

(vii) The use of the quick-reading potentiometer greatly facilitated the measurement of the rise of temperature in the calorimeter, owing to (*a*) the speed with which a balance could be obtained, and (*b*) the immunity of the instrument from the vibration of the furnace floor.

(viii) Experience has shown that the present single-calorimeter instrument can be turned over easily, and thus no increase in the rapidity of readings with a manually operated instrument could be gained by having two calorimeters facing in opposite directions. Two calorimeters would have the effect of increasing the work of the operator of the control bench, who is at present kept fully occupied, and of reducing that of the operator who holds the instrument in the furnace and whose time is, under present conditions, not fully utilized. This does not mean, however, that two calorimeters are undesirable in all cases. If the instrument were ever required for automatic operation, recording the results directly upon a chart, then a definite advantage would be derived from the use of two calorimeters. Also, if interest

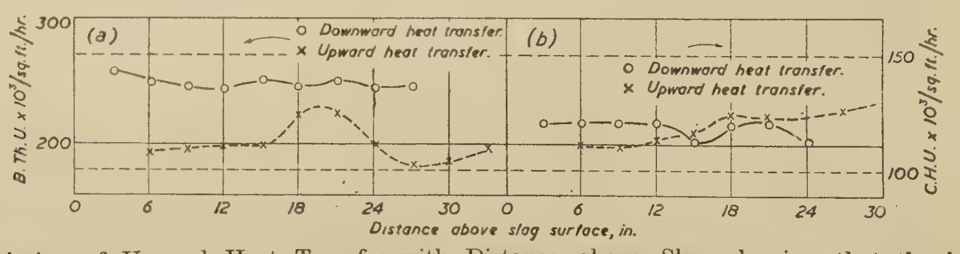


FIG. 30.—Variation of Upward Heat Transfer with Distance above Slag, showing that the importance of measuring the upward heat flow very close to the slag surface is not as great as the Samuel Fox works. Flame travelling (*a*) from right to left, and (*b*) from left to right. (Furnace *K*.)

were centred mainly on the net heat transfer and not on the total heat transfer, the use of two calorimeters with water flow in series and a pair of opposed differential couples would be an advantage. It is possible that an instrument could with advantage be designed for use as standard equipment in a steel-melting shop, to be inserted rapidly into any furnace where there was doubt as to the heating power. Such an instrument would probably be used for measuring net heat transfer.

Heat Flow in the Glass-Tank Furnace.

(a) *Comparison of Radiation at Ingoing and Outgoing Ends.*—The average value of the downward heat transfer on the axis of the first port is greater for half-cycles when the instrument is near the incoming end of the flame. The average drop in downward radiation is 11% for producer-gas firing and 16% for creosote-pitch firing. This by itself does not mean that the downward heat transfer on the outgoing side, taken over the whole length of the bath, is less than that on the incoming side, since it might well be that the flame was covering a greater bath area. What does determine the relative heating powers of the two ends of a flame is the area under the curve showing the relation between downward heat transfer and distance across the furnace at right angles to the gas flow. The curves showing this relation do, however, indicate that the downward heat transfer at the incoming end of the flame is the greater.

The difference between the two readings for different gas flames varies between 4 and 19% of the reading at the incoming end of the flame. It would be interesting if this could be correlated with the hydrogen content of the producer gas, with a change in the gas/air ratio, or with a change in the volume of gas entering the furnace. A fuller understanding of the relevant variables would make it possible to obtain a producer-gas flame giving a maximum of useful heat transfer.

(b) *Variation of Downward Heat Flow during Half-Cycle.*—There is, on the whole, a tendency for the observed downward heat flow to fall off during each half-cycle, it being usually 5 or 10% lower at the end than at the beginning. This may be partly an instrumental effect, as in some of the tests the calorimeter was reblackened only at the end of each half-cycle, but the same effect appears to have occurred even when it was reblackened every 10 min. It seems likely, therefore, that this effect results from a change in temperature of the flame due to the progressive cooling of the regenerators during the half-cycle.

The opposite tendency is observed in about one-third of the cases; in all cases where this occurs (*i.e.*, where there is a slight increase during the half-cycle of the observed downward heat flow) there is also a much greater increase in the upward heat flow. This correlation between the downward heat flow and the reradiation from the glass is a point of considerable interest. The three most obvious explanations are: (*a*) Reflection of heat from the crown, (*b*) the effect of the cold batch upon the rapidity of the combustion in its immediate neighbourhood and hence upon the local heat release, and (*c*) the effect of the cold batch upon the luminosity of the flame in its neighbourhood. The second of these explanations is the most likely to be correct, because the piles of batch are of small dimensions compared with the height of the crown, and also because there is evidence that the flame is fairly opaque. This is analogous to the effect of lining the first few feet of the flue of a Lancashire boiler with refractory in order to obtain satisfactory combustion with pulverized fuel.

(c) *Net Heat Transfer to Stock.*—The reradiation from the stock depends entirely on the condition of the stock itself, *i.e.*, on the presence or absence of floating batch. The net heat transfer to the batch piles may be up to five times as much as that to the clear molten glass. This suggests that a greater increase in the melting rate is likely to be obtained by feeding a thin layer of batch over the whole glass surface, leaving the space underneath for mixing, &c., than can be obtained by making the flame perfectly opaque.

(d) *Variation of Downward Heat Flow across the Width of the Furnace.*—The downward heat flow shows a very marked local increase at the incoming end of the flame, as the instrument is moved under the axis of the flame, whereas it is almost uniform at the outgoing end. This may be due to the spreading-out of the flame jet, as was observed in a cold furnace by Gooding and Thring.[13]

(e) *Readings near the Crown.*—The reading obtained with the instrument above and facing the flame was almost exactly the same as that obtained with it below and facing the flame. This suggests that the flame is rather opaque. The fact that the reading obtained with the instrument facing the crown increases rapidly immediately after the reversal, indicates either that the temperature of the inner surface of the crown closely follows the effective local flame temperature, or that the crown is appreciably reflecting.

Heat Flow in the Open-Hearth Furnace.

Comparison of Downward Heat Flow at the Incoming and Outgoing Ends of the Flame.—As determined at the works of Messrs. John Summers & Sons, Ltd., the downward heat flow is greater under the central axis of the incoming end of the flame than at the outgoing end—the same result as was found in the glass-tank furnace. As has already been explained, this does not necessarily mean that the heating power at the in-

coming end of the furnace is greater than that at the outgoing end; but the curves giving the variation of downward heat flow at both ends indicate that in general there is a slightly greater total heating power under the incoming end of the flame when averaged across the width of the furnace.

The reverse appears to be true at the works of Messrs. Samuel Fox & Co., Ltd. Here there are periods when the curves at the outgoing end give the higher downward transfer. The test position was only 7 ft. 6 in. from the gas port, and hence at the incoming end combustion was probably very incomplete; this may account for the lower reading. At the John Summers works the tests on the end doors were taken at a distance of 9 ft. 6 in. from the port. It would be interesting to know whether the same phenomena are observed at a similar distance from the gas port at Samuel Fox's works.

The curves in Fig. 22, taken at the John Summers works, illustrate how the instrument can be used to diagnose an "out-of-balance" furnace. The downward heat transfer from the incoming end (*viz.*, left, or door No. 1) of the left–right flame is the same as that from the incoming end (*viz.*, right, door No. 3) of the right–left flame. On the other hand, at the outgoing end (*viz.*, right, door No. 3) the left–right flame gives a slightly lower transfer than the outgoing end (*viz.*, left, door No. 1) of the right–left flame. This contrast implies that the left–right flame is slightly shorter than the right–left flame, as was confirmed by readings at the middle door. The out-of-balance is not so noticeable on the other curves.

Variation of Reading with Time.—The fact that the reading decreases with time indicates that deposits build up on the calorimeter face. This may be due either to particles of slag or to the thickness of the carbon deposit increasing. However, this difficulty was overcome by cleaning the surface of the calorimeter between pairs of readings. It is interesting to note that the outlet temperature of the cooling arm dropped from 60° to 50° C. during a 20-min. insertion. The arm was actually seen to be covered with slag droplets, which would appear to be the cause of the fall in the reading. This suggests that it might be possible to reduce the water quantity required to cool the main supporting arm by coating it with slag.

Variation of Actual Downward Heat Flow with Time.—At the John Summers works the variation of the downward heat flow with time is sensibly constant during the refining period. At the Samuel Fox works the downward flow is more erratic, but still there is no general tendency for it to fall or rise towards the tapping time. Nevertheless, there is a definite tendency for the net heat transfer to the charge to fall off towards the tapping time. This is just as would be expected, and is clearly shown in Fig. 28.

Reradiation from the Slag Surface.—At both steelworks the reradiation from the slag (upward heat flow) follows the downward transfer very closely. This indicates either that the slag is highly reflecting or that the surface temperature of the slag follows that of the flame. A similar observation relating to the crown of a glass-tank furnace has already been noted. In spite of this effect the net heat transfer is higher, other things being equal, when the total downward heat flow is higher.

Variation of Downward Heat Flow across the Furnace.—At both works a decided rise in downward heat flow was noted at a definite distance across the furnace. At the John Summers works this change occurs about 4 ft. 6 in. from the centre line, and at the Samuel Fox works at 2 ft. from the centre line. Probably the change occurs at the point at which the calorimeter enters the flame.

Variation of Magnitude of Downward Heat Flow.—The curve of Fig. 22(*b*) stands out from the others because the exceptionally high downward heat flow showed that in the variation across the width of the flame the transfer is sensibly normal within about 4 ft. from the outside of the furnace. The calorimeter was within the furnace wall from 4 ft. up to about 2 ft. 6 in. from the outside of the furnace. It would thus appear that the sudden increase occurs at the point of entry into the flame. At the Samuel Fox works, also, high readings were observed, but not as high as those referred to above.

Relative Values of Heat Flow Above and Below the Flame.—The upward heat flow measured close to the roof is comparable to the downward heat flow close to the slag. This means either that the values of the radiation from the slag surface and from the roof are practically the same, or that the flame is relatively opaque.

Variation of Upward Heat Flow with Height above Slag Surface.—At the John Summers works the value of the reading falls off very rapidly in the last foot nearest to the bath. This may be due either to the gradual elimination of convection as the instrument is lowered, or to the fact that, as the instrument is raised, the flame becomes opaque at a thickness of about 1 ft. At the Samuel Fox works this falling off at the slag surface does not occur except in one case, and here it is thought that the calorimeter became covered with slag. This explains why it was essential to dip the calorimeter into the slag to obtain the downward reading at the John Summers works, whereas this was unnecessary at the Samuel Fox works. It also shows that special techniques must be devised at different works to meet the differing furnace conditions.

Another fact worth noting is that the flame in the furnaces at the John Summers works appears (visually) to be more fierce that that at the Samuel Fox works, suggesting that the convection may be greater at the former. However, no final conclusion can be drawn until the radiation has been separated from the convection.

Heat Transfer to the Roof.—The readings close to the roof show, as would be expected, a net transfer to the roof which is not very different from the net transfer to the bath.

Net Heat Transfer During Absence of Flame.—At the Samuel Fox works several pairs of readings were taken during a reversal when there was no flame in the furnace. In these cases there was a small apparent net heat transfer away from the slag surface. This suggests that the slag surface is at a slightly higher temperature than that of the crown, showing that the objective of heating the slag to a temperature beyond the limitation set by the crown is to some slight extent achieved.

Conclusions from the Experimental Results as to the Mechanism of Heat Transfer in Furnaces.

Factors Affecting the Net Heat Transfer to the Charge.—While, from the work described in this paper, it is not possible to indicate clearly the separate contributions to the heat transfer in a furnace of radiation and convection, certain tentative conclusions can be drawn which may serve as a basis for discussion.

In the first place, readings taken in steel and glass furnaces at various positions across the width of the furnace and close to the slag surface, suggest a distinction between the general furnace radiation H_0 and the flame radiation $H_0 + \Delta H$ (ΔH is a positive quantity). The general furnace radiation H_0 is that measured (1) when the flame is off, (2) when the meter is near the roof and facing it, or (3) when it is near the charge, but not under the intense part of the flame. In the glass-tank furnace (Fig. 13) H_0 has the value 61,000 C.H.U./sq. ft./hr., and in the steel furnace (Fig. 29(*b*)) about 100,000 C.H.U./sq. ft./hr. This general furnace radiation corresponds closely to the radiant temperature of the melted glass in the one case and to that of the slag surface in the other. Hence the only useful heat transfer to the already-melted materials is that which occurs where the flame radiation exceeds this "null value" by an appreciable quantity, *i.e.*, where ΔH is appreciable.[13] This conclusion is confirmed by the readings taken with the instrument facing downwards, which indicate that the net heat transfer is very small except in the regions where the flame radiation appreciably exceeds that of the general furnace. In a recent paper Fisher mentions that he has measured the radiation from a hole in the door with a total-radiation pyrometer, and adds "the difference between the high and low readings represents the amount of heat transferred from the flame to the bath."

We shall attempt to draw some conclusion from the experiments as to the important quantity ΔH. The producer-gas flame is long and at the outgoing end usually gives an appreciable value for ΔH right across the furnace. This agrees with the expectation that the flame would spread as a jet with the well-known Tollmien angle [13] and that combustion is governed by the drawing into the gas-jet of the slower-moving air.[14] In one case (a curve obtained at the Samuel Fox works) the quantity ΔH is actually greater at the outgoing than at the incoming end. With creosote pitch the value of ΔH at the incoming end exceeds that at the outgoing end by an amount greater than with producer gas.

The results of the distribution of radiation at the incoming end (Fig. 13 for the glass-tank furnace and Fig. 23 for the open-hearth furnace) are even more interesting. They indicate that combustion takes place in the gas-jet but not in the air stream; for example, in the open-hearth furnace (where the air surrounds the gas) the radiation only exceeds that of the general furnace under the gas, so that the area of the bath under the air is wasted. Similarly, in a glass-tank furnace the area between the ports is useless for heat transfer. This conclusion that combustion takes place in the gas-jet and not in the surrounding air space is again in agreement with the theory of jets, which indicates [15] that a high-velocity jet issuing from an orifice draws in the surrounding gas and in so doing gradually dissipates its own kinetic energy. A tentative, but possibly important, suggestion relating to the design of steel furnaces arises from the fact that just where the flame has the best radiating power (the first half of its path in the furnace) it is confined to a relatively small useful heat-absorbing area, say, the central one-third of the bath. A wider flame would increase the useful heat absorption of a bath of given size very appreciably.

A further conclusion can be drawn relating to the quantity ΔH. During the melting period of the steel furnace, and in the region of unmelted batch of a glass furnace or, in fact, in any furnace where the roof temperature appreciably exceeds the charge temperature, good heat transfer can be obtained with a flame which merely suffices to keep the furnace up to temperature. During the refining period of a steel furnace or over the melted glass in a glass-tank furnace, on the other hand, it is clear from these results that the difference between a good and bad flame lies entirely in the part by which it exceeds the general furnace radiation, which may be relatively small. Hence, a small percentage increase in the flame radiation, whether it results from an increase in temperature or in emissivity, is of very great importance.

Methods of Increasing the Heat Transfer to the Charge without Increasing that to the Crown.—In the high-temperature reversing furnace one of the greatest problems is that of increasing the heat transfer to the charge without overheating the crown. This is especially true in the open-hearth furnace, where there is only some 50° C. difference between the working bath-temperature and the melting point of the crown. The results already given and the evidence set out in Appendix IV. suggest that convection is unlikely to be responsible for more than 10% of the heat transfer and hence is relatively unimportant. The aim of the usual port system is to produce a jet of high-velocity flame projected downward on to the charge in order to obtain a greater heat-transfer coefficient by convection to the charge than to the crown. However, since radiation is probably responsible for 90% of the actual heat transfer, the crown will be subjected to an effective flame temperature almost identical to that which heats the charge, the intervening layer of air being almost completely transparent. Moreover, this air has a relatively low velocity, so that even if it is much cooler than the flame it will not cool the crown appreciably by convection. This form of cooling is greatly to be preferred to external cooling since heat taken up by the air inside the furnace would later be available to the flame.

This leads to a tentative suggestion as to how the crown might possibly be kept at the present temperature while the heat transfer to the charge is increased. This is most likely to be achieved by interposing a blanket of cooler non-transparent gas between the hottest part of the flame and the crown. One possible way of doing this would be to allow the gas to pass along the furnace in a slow-moving thick stream while the air is introduced, so as to give rapid mixing in two or three separate streams along the furnace just above the charge level. In this way a luminous, cooler flame would be interposed between the very intense local flames and the crown. It is recognized that such an arrangement would offer very great practical difficulties, but it is no more revolutionary than a proposal made in last year's American Open-Hearth Conference [16] to have multiple air–oil burners along the sides of the furnace. However this may be, the main purpose of the present paper is to show the kind of information that can be obtained with a heat-flow meter, in the hope that others will build and use such instruments, thereby obtaining information of value to the furnace-using industries.

Acknowledgments.

The authors have pleasure in acknowledging the help and encouragement they have received from the following: Dr. R. J. Sarjant, who originally drew attention to the need for an instrument capable of measuring heat flow in industrial furnaces; Messrs. John Summers & Co., Ltd., and Mr. F. L. Robertson and Mr. C. W. J. Crawford who provided facilities for the work carried out at Shotton; Messrs. Samuel Fox & Co., Ltd., and Mr. Crooks and Mr. Tyler, who allowed the experiments to be carried out at Stocksbridge; Mr. Wardley of the Rockware Glass Syndicate who, as Chairman of the B.C.U.R.A. Heat-Flow-Meter Panel, has been a source of inspiration throughout the work and who, with his colleague, Dr. Gooding, has given much practical advice on the question of design; The United Glass Bottle Manufacturers, Ltd., and members of their Research Laboratory and Works Staff; Dr. M. Fishenden, who has given valuable advice on the theory of the instrument; Mr. Dall of Messrs. George Kent, Ltd., and Mr. Forster of B.C.U.R.A. who have provided valuable assistance with the design of the instruments and auxiliary apparatus employed in the investigation; and Mr. Cooper of B.C.U.R.A. for assistance in editing the paper.

Appendix I.—*Checks on the Absolute Accuracy of the Instrument.*

Although once the thermocouples and flow gauge have been calibrated the instrument itself constitutes an absolute radiometer, it was thought useful to compare its readings with the temperature readings obtained in a black-body enclosure. For this purpose it was necessary to obtain an enclosure which could be heated to a temperature exceeding 1200° C., while being substantially uniform in temperature, and which was large enough not to be appreciably cooled by the insertion of the instrument.

The furnace used was a small high-temperature coke furnace having an inner chamber, which was approximately a 2-ft. cube, with fuel at the base. By shutting off the air and closing the gas vent, fairly uniform temperatures could be attained within the chamber. The furnace possessed a fairly large heat capacity in relation to its size.

The furnace was heated up to about 1450° C. and then the instrument was inserted to a distance of 6 in. with the calorimeter facing one of the vertical walls. After conditions had become fairly steady the air supply was turned off and readings of the instrument and of the furnace temperature were taken as the furnace cooled down. The temperature of the furnace was measured on the wall facing the calorimeter, in two places with an optical pyrometer and in two other places with platinum thermocouples.

The principal sources of error are: (1) The measurement of the temperature (possible error up to about $\pm 3\%$), and (2) uneven temperature distribution in the furnace. Also, the insertion

of the cold instrument into the chamber causes the black-body conditions to be upset, but it is not anticipated that the resultant error is very great.

The tests, the results of which are given in Table III., show that the instrument reading is usually below the calculated value; this would be expected, as the surface of the calorimeter can never be perfectly black. However, the tests show that if the instrument is assumed to have an emissivity of 96%, then the readings can safely be taken to have an absolute accuracy well within $\pm 3\frac{1}{2}\%$. The relative accuracy of readings taken one after the other with the calorimeter facing first up, and then down, is very much better than this. Hence it is probable that where the difference between these two readings is 10% of one of them, the accuracy in determining the difference is of the order of $\pm 10\%$ (*i.e.*, $\pm 1\%$ of the separate readings).

TABLE III.—*Comparison of Actual Reading and Calculated Values.*

Time.	Furnace Temperatures, °C.				Mean Temp., °C.	Calculated C.H.U. × 10^3/sq. ft./hr.	Measured, C.H.U. × 10^3/sq. ft./hr.	Percentage Difference.
	Optical Pyrometers.		Thermocouples.					
	No. 1.	No. 2.	No. 1.	No. 2.				
4–18	1290	1310	1325	1238	1290	60	60·5	+1
19	1260	1270	1310	1234	1268	56·5	56·5	0
20	1270	1280	1297	1234	1270	57	55·5	−3
21	1270	1270	1275	1230	1261	55	52·2	−6
22	1250	1255	1250	1230	1246	53	50	−6
23	1210	1220	1245	1225	1225	50	48·7	−3
25	1200	1295	1238	1215	1237	51	46·4	−7
27	1180	1180	1215	1200	1194	46	45	−2
29	1160	1150	1200	1185	1174	43	42	−2
31	1170	1160	1185	1177	1173	43	40	−6
4–50	1400	1350	1245	1200	1300	62	61	+2
51	1340	1260	1245	1200	1280	58	59	+2
52	1280	1230	1230	1238	1245	53	54	+2
53	1260	1220	1223	1193	1225	50	52	+4
54	1250	1210	1215	1185	1215	49	50	+2
55	1240	1210	1200	1185	1210	48	48·5	+1
56	1230	1210	1200	1178	1205	47	46·5	−3
57	1230	1220	1185	1178	1203	47	45	−4
5–00	1210	1200	1170	1170	1190	44	43	−2
2	1200	1190	1155	1163	1175	43	41	−4
4	1190	1150	1150	1155	1160	42	41	−2
6	1170	1130	1135	1140	1145	40	37·5	−5

APPENDIX II.—*Description of a Glass-Tank Furnace of the Type used in the Authors' Experiments.*

The furnace (Fig. 11) is fired by producer gas generated from bituminous coal in a separate gas producer. Both air and gas are preheated in brick regenerators to a temperature of between 900° and 1200° C. The furnace is also arranged so that it can be converted to creosote-pitch firing in an emergency, or when the gas-producer equipment requires cleaning. The melting chamber is rectangular in plan, with three gas–air ports in each side wall. Each of the two sets of ports is connected to a pair of regenerators, one for air and the other for gas. The flames pass for $\frac{1}{2}$ hr. in one direction across the furnace and for the next $\frac{1}{2}$ hr. in the reverse direction. The furnace temperature is controlled by varying the quantity of gas consumed. The gas enters below the air so that the hydrogen, which tends to rise, will produce more efficient mixing and combustion.

The crown, which is insulated, is built up of a 12-in. thickness of silica arch, spanning the whole width of the furnace.

The batch is introduced at $\frac{1}{2}$-hr. intervals through a special door in the " melting end " from a chamber called the " dog-house." This batch floats in piles on the surface of the molten glass. The depth of the glass in the furnace is about 42 in. and the finished glass is drawn through a throat at the opposite end. The general flow of material is thus at right angles to the three flames, but the floating piles of batch move in a rather random manner.

APPENDIX III.—*Comparison of Different Operating Conditions at the two Steelworks.*

Works of Messrs. John Summers & Sons, Ltd., Shotton.

Fig. 17 shows the port designs used during the period covered by the paper. All the furnaces tested were constructed as shown in Fig. 17(*a*), except furnace *R*, which was arranged as indicated in Fig. 17(*b*) until July, 1944, when it was brought into line with the others. The gas port is roughly

18 in. sq., and the air enters on both sides of it, but not over the top. The reversals of the flame direction take place according to time, the usual duration of a half-cycle being 10 min., but in some cases this is extended to 12 min.

The crown temperature of all furnaces is recorded by means of a total-radiation pyrometer attached to an automatic recording potentiometer or millivoltmeter. Most furnaces have two pyrometers, one being sighted on each end of the crown, but both recording on a single chart such as that shown in Fig. 31, which is typical of the curves obtained during a melt. The remainder of the furnaces are fitted with a single pyrometer, which is sighted on the centre of the crown midway between the two ports. Fig. 32 shows a single-pyrometer roof chart.

The melters have instructions to raise the roof temperature as quickly as they can to the highest safe temperature (1640° C.) and to maintain it as far as possible at that value throughout the period from " level " to " tapping." On furnaces fitted with two pyrometers, the melter has to aim at maintaining the readings of both at this temperature, without permitting either to exceed it, and with good operation it is possible to keep to

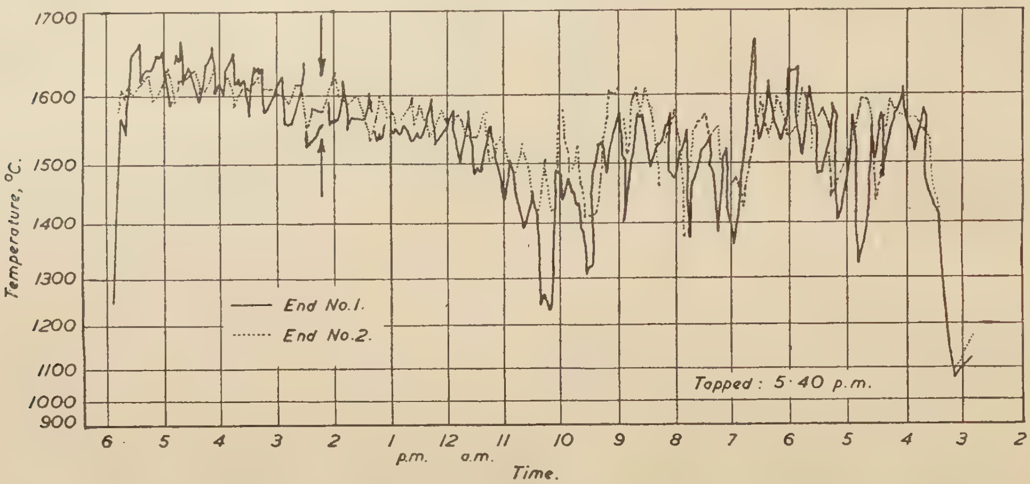


Fig. 31.—Typical Roof Chart, using Double Pyrometer.

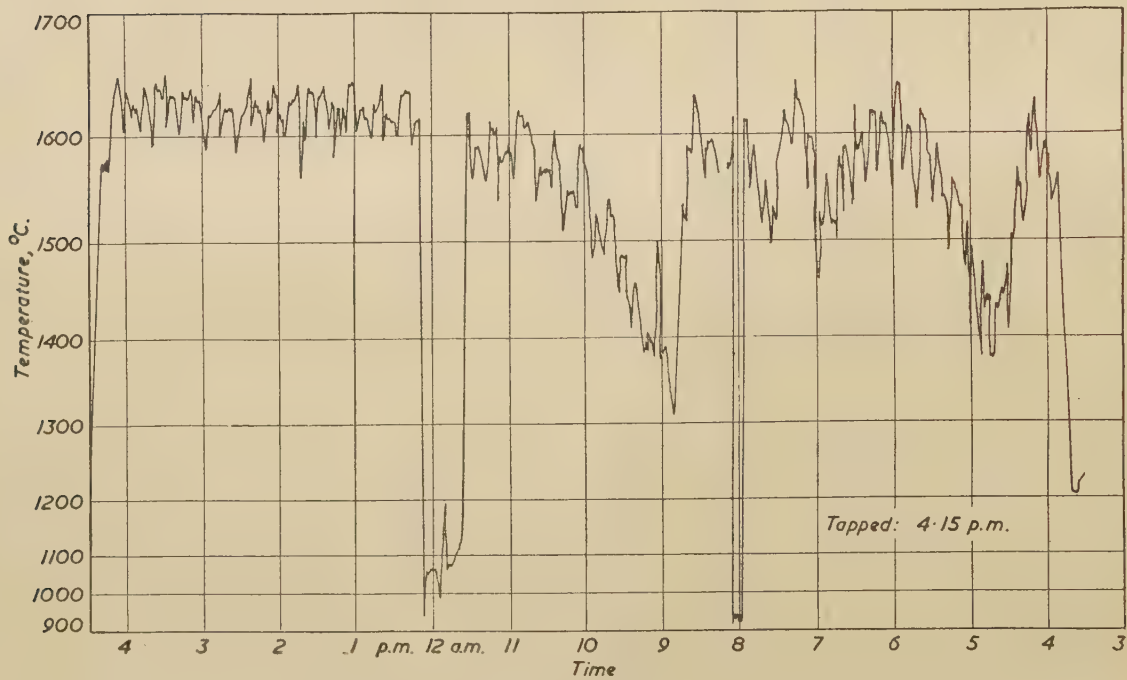


Fig. 32.—Typical Roof Chart, using Single Pyrometer.

within 20° C. The pyrometers are calibrated against a disappearing-filament pyrometer at intervals of approximately ½ hr.

The amount of slag required to reduce the sulphur content of the resulting steel to the desired percentage is largely dependent on the quantity of silica present. The John Summers works find that they require a slag depth of 9 in.

All furnaces are fitted with three water-cooled doors through which the charge is introduced. Each of these doors has two sight-holes, situated at approximately 1 ft. and 4 ft. above the slag

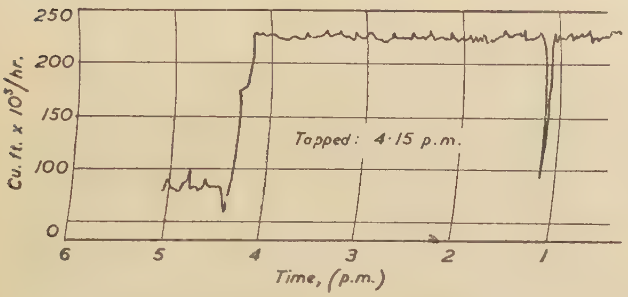


FIG. 33.—Typical Gas Chart.

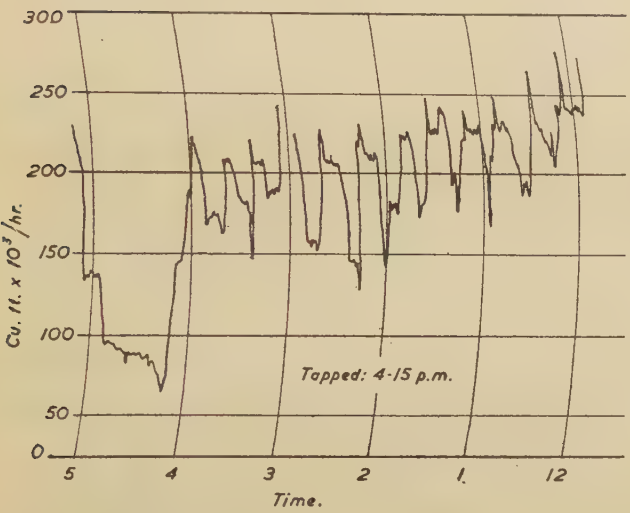


FIG. 34.—Typical Air Chart.

surface. In general, the only purposes for which the doors are raised are for charging, feeding, sampling, and stirring. Only in comparatively exceptional circumstances are the doors raised for examination of the furnace conditions, most of which can be done through the sight-holes.

Many of the furnaces are fitted with small "port" doors, about 2 ft. sq., situated just in front on the gas port. In the earlier tests this door also was water-cooled, but later a brick door was substituted.

Typical air and gas charts obtained during the period of insertion of the heat-flow meter are shown in Figs. 33 and 34.

Works of Messrs. Samuel Fox & Co., Ltd., Stocksbridge.

The gas port is built into a Venturi-shaped throat, through which the combustion air is supplied. The method differs from that used at the John Summers works in that air is introduced above the gas port as well as on either side.

The general rule is that reversal of flame direction is carried out according to the temperature of the checkers, but owing to rapid changes in the working of the charge, particularly during refining, this cannot be strictly enforced.

A total-radiation pyrometer is sighted on to the centre of the crown midway between the two ports, as at the John Summers works. This pyrometer is at present in the experimental stage, and is not intended to serve as a control instrument.

The slag thickness used is of the order of 2½ in., which is very much less than that required by the John Summers works, but the area of the hearth is greater, being about 420 sq. ft. for roughly the same capacity.

The furnace on which the tests were carried out was fitted with five doors, the two outer ones of brick, and the remaining three water-cooled. The doors, being without sight-holes, had to be opened each time to check the furnace conditions.

APPENDIX IV.—*Calculated Heat Transfer in the Open-Hearth Furnace.*

Radiation.

The radiation values from a black body at T° C. and from a flame at T° C. with an emissivity of 0·5, backed by a black wall at 1600° C., are given in Table IV.

TABLE IV.—*Radiation from a Black Body and a Flame of Emissivity* 0·5, *both at* T° *C.*

Temp., °C.	Black-Body Radiation, C.H.U./sq. ft./hr.	Total Downward Radiation from Flame of Emissivity 0·5 and Crown at 1600° C., C.H.U./sq. ft./hr.
1300	69,000	...
1400	79,000	...
1500	100,000	...
1550	113,000	...
1600	125,000	125,000
1650	138,000	131,500
1700	159,000	139,000
1750	169,000	147,000
1800	187,000	156,000
1900	226,000	176,000
2000	270,000	198,000

By the use of this Table the radiation from a flame to a charge which is at 1600° C. has been calculated as a function of flame temperature, with the results given in Table V. (E is the effective emissivity of the combination of flame, crown, and charge.)

Convection.

It is usually assumed that the coefficient of convection in a furnace is independent of the gas velocity. For example, Schack [17] gives a figure of 1·5 C.H.U./sq. ft./hr./°C. for the convection in an open-hearth furnace. A more reasonable assumption would seem to be the use of the formula for heat transfer by forced convection to a plate,[18] namely:

$$\alpha = 0{\cdot}52 V^{0\cdot78} \text{ B.Th.U./sq. ft./hr./°F.},$$

or a rough surface in air at 68° F. For hot gases at 1600° C., it follows from similarity theory that α will be altered by the factor $\left(\frac{k}{k_0}\right)^{0\cdot22}\left(\frac{c}{c_0}\right)^{0\cdot78}$, which is of the order of 0·37.

TABLE V.—*Calculated Radiation from a Flame at T° C. and Various Emissivities.*

Temp. (*T*) of Flame, °C.	Net Radiation to Charge, C.H.U./sq. ft./hr.		
	E = 0·5.	*E* = 0·7.	*E* = 0·9.
1650	6,600	9,100	12,000
1700	14,000	19,600	25,000
1750	22,800	31,900	41,000
1800	31,100	43,000	56,000
1850	40,300	56,500	72,300
1900	50,500	70,600	91,000
1950	61,200	85,600	101,000
2000	73,000	102,000	131,000

TABLE VI.—*Net Heat Transfer to Charge by Convection, in C.H.U./sq. ft./hr.*

Flame Temp., °C.	*V* = 20 ft./sec.	*V* = 40 ft./sec.	*V* = 60 ft./sec.
1650	100	170	230
1700	200	340	460
1750	300	510	690
1800	400	680	920
1850	500	850	1,150
1900	600	1,020	1,380
1950	700	1,190	1,610
2000	800	1,360	1,840

In this way values of α were calculated for three mean hot-gas velocities such as are likely to occur in practice. It was found that for $V = 20$, 40, and 60 ft./sec., respectively, the corresponding values of α were 2·0, 3·4, and 4·6 C.H.U./sq. ft./hr./°C. These values are somewhat higher than those of Schack. Table VI. gives the values of the heat transfer by convection corresponding to these velocities and to the same temperatures as Table V.

A comparison of Tables V. and VI. shows that the heat transfer by convection will be between 1 and 3% of the total, but will probably be nearer 1 than 3%.

REFERENCES.

1. HÄSE: *Archiv für Warmewirtschaft und Dampfkesselwesen*, 1932, vol. 12, p. 317.
2. STOFFREGEN: *Archiv für das Eisenhuttenwesen*, 1932–33, vol. 6, p. 271.
3. CROFT and SCHMARJE: *Transactions of the American Society of Mechanical Engineers*, 1935, vol. 57. p. 105.
4. ORROK: *ibid.*, 1925, vol. 47, p. 1148.
5. WOHLENBERG and MORROW: *ibid.*, 1925, vol. 47, p. 127.
6. CROFT and SCHMARJE: *ibid.*, 1936, vol. 58, p. 117.
7. HOTTEL, MEYER, and STEWART: *Industrial and Engineering Chemistry*, 1936, vol. 28, p. 708.
8. STYRIKOWITSCH: *Technical Physics of the U.S.S.R.*, 1936, vol. 3, p. 197.
9. KAZANTSEV: *Stal*, 1939, No. 9, p. 25.
10. FISHENDEN and SAUNDERS: "The Calculation of Heat Transmission," p. 141, formula (51). London, 1932: H.M. Stationery Office.
11. LEWIS and VON ELBE: *Journal of Applied Physics*, 1940, vol. 11, p. 698.
12. SCHOFIELD and GRACE: *The Iron and Steel Institute*, 1939, *Special Report No.* 25, p. 239.
13. GOODING and THRING: *Transactions of the Society of Glass Technology*, 1941, vol. 25, p. 21.
14. FISHER: *American Institute of Mining and Metallurgical Engineers*, 1944, *Open-Hearth Proceedings*, p. 116.
15. DAVIS: *Transactions of the Institution of Mechanical Engineers*, 1937, vol. 137, p. 11.
16. SEIL: *American Institute of Mining and Metallurgical Engineers*, 1944, *Open-Hearth Proceedings*, p. 59; *Industrial Heating*, 1944, vol. 11, p. 1289.
17. SCHACK: *Mitteilungen der Wärmestelle*, 1923, No. 55.
18. FISHENDEN and SAUNDERS: "The Calculation o Heat Transmission," p. 141, formulæ (49)–(51). London, 1932: H.M. Stationery Office.

For Discussion on this Paper, *see* the *Journal*, 1946, No. II.

THE REMOVAL OF HYDROGEN FROM STEEL.*

By Professor J. H. ANDREW, D.Sc., F.I.M., H. LEE, B.Eng., Ph.D., A. K. MALLIK, B.Met., B.Sc., Ph.D., and A. G. QUARRELL, D.Sc., F.Inst.P., F.I.M. (The University, Sheffield).

Paper No. 22/1946 of the Alloy Steels Research Committee (submitted by the Hair-Line Crack Sub-Committee).

(Figs. 10 to 13 = Plate II.)
(Figs. 50 to 57 = Plates III. and IV.)

Synopsis.

A systematic investigation of the removal of hydrogen from a number of steels under isothermal conditions has been carried out, and it is shown that, for all steels, the rate of removal in the intermediate range is high, and that, for certain steels, there is also a peak on the removal curve corresponding to transformation in the pearlitic region. The law governing hydrogen removal in the austenitic range has been determined experimentally, and the empirical relationship supported by theoretical treatment. The effect of transformation upon the removal of hydrogen is illustrated, and the effect of specimen size is also dealt with. It is shown that small partial pressures of hydrogen surrounding the steel at 1100° *C. exert a considerable retarding effect upon the removal of hydrogen, although, as might be expected, this effect becomes quite small at* 650° *C.*

In the presence of hydrogen the transformation of a nickel–chromium–molybdenum steel was retarded in the range 600–450° *C., but little effect was observed at lower temperatures. Comparison of the rate of diffusion of hydrogen through similar specimens of different steels showed that alloying elements have little, if any, effect upon the diffusion constant. This was confirmed in the austenitic range by the results obtained for the law of hydrogen removal. The evolution of hydrogen on cooling was followed, and it was found that the maximum rate of evolution corresponded to the end of the thermal transformation.*

The mechanical properties of a large number of steels have been determined after treatment in hydrogen and nitrogen, and it is shown that the embrittling effect of hydrogen is apparent in all cases where the hydrogen content is 1·0–3·0 *c.c./*100 *g.*

In connection with the work on the removal of hydrogen, much evidence has been obtained upon the formation of hair-line cracks under various conditions. It was found that such cracks could appear in the absence of transformation stresses, and that these stresses are important mainly in that they determine the particular crack distribution which results. Although no cases were observed of internal crack formation in the absence of hydrogen, certain specimens showed no cracks in spite of a high hydrogen content. The view of the hydrogen-rich constituent put forward in a previous paper has been modified, in that it is not now considered to be necessarily austenitic; it is realized that at the moment of crack formation the steel will be in an extremely brittle condition, owing to its hydrogen content. The exact nature of the hydrogen-rich constituent cannot be given, nor can a detailed explanation of hair-line crack formation be expected, until the much wider problem of low-alloy steels in general is more thoroughly understood.

The discussion to which an earlier paper [1] gave rise showed that most steelmakers were aware of the detrimental effect of hydrogen upon steel, and that the question of the removal of hydrogen by heat-treatment was one of immediate practical importance.

The work now to be described was undertaken in order to determine the temperature at which hydrogen could most readily be removed, and in what way this temperature depended upon the composition of the steel. At the same time much information has been obtained concerning the formation of hair-line cracks, particularly under conditions not investigated in the earlier work.

All experiments have been carried out on normal commercial steels, the analyses of which are given in Table I.

Hydrogen Removal by Isothermal Treatment.

Although many workers have suggested involved heat-treatments for the prevention of hair-

* Received August 13, 1945. This paper is published by authority of the Alloy Steels Research Committee. The views expressed in it are the authors' and are not necessarily endorsed by the Committee as a body.

line cracks, little work appears to have been reported in which the effect of heat-treatment has been systematically explored from the point of view of hydrogen removal. The simplest methods suggested for the prevention of hair-line cracks have involved slow cooling of the billet or forging after hot-work, but the rate of cooling necessary for a given steel of a definite cross-section has been determined only as a result of experience. When a new steel has been introduced, much work has been necessary before the minimum heat-treatment for the prevention of cracks could be specified. Owing to the uncertainty of the hydrogen content of steel ingots and the complex nature of steelworks practice, it is extremely difficult to make a direct comparison between steels of different compositions and their susceptibility to hair-line crack formation. This may account for the divergent opinions expressed by prominent steelmakers as to the best treatment for the prevention of hair-line cracks in specific cases.

Bearing these facts in mind, it was desirable to develop an experimental technique by which it would be possible to follow the removal of hydrogen from different steels during heat-treatment under laboratory conditions. It was considered that the experimental conditions could be controlled more rigorously and that the results were likely to be of wider practical application if the removal of hydrogen was investigated at constant temperature rather than at different rates of cooling.

For the investigation of hydrogen removal under isothermal conditions, it was considered that:

(1) Two specimens of the same steel should be prepared with an equal hydrogen content. This hydrogen content should be at least 5 c.c./100 g. of steel (this notation will be used throughout).

(2) The specimens should be quenched in a lead or salt bath of sufficient capacity to ensure rapid cooling without an undue rise in temperature of the bath.

(3) The time allowed to elapse before the first specimen is quenched from the lead or salt bath should be sufficient to ensure that when the hydrogen content is determined it may be regarded as the initial content of the steel at the temperature of isothermal treatment.

(4) The second specimen should be held in the isothermal bath for a suitable period of time and then quenched in brine to enable the "final" hydrogen content to be found.

These requirements have been fulfilled by the following experimental arrangements:

Table I.—*Analyses of Steels Used in the Experiments.*

Steel.	C, %.	Si, %.	Mn, %.	P, %.	S, %.	Ni, %.	Cr, %.	Mo, %.	V, %.
4S11	0·33	0·22	0·57	0·027	0·034	3·18	0·70	0·23	...
FA	0·29	0·20	1·45	0·019	0·024	...	...	0·26	...
CM	0·19	0·20	0·54	0·013	0·015	0·25	3·06	0·44	...
HD	0·24	0·24	0·52	0·019	0·020	0·22	3·35	0·54	...
NV	0·46	0·23	0·67	0·027	0·030	2·35	0·18	0·14	0·12
V30	0·27	0·23	0·63	0·015	0·016	2·57	0·64	0·61	...
K6	0·61	0·28	0·73	0·032	0·047	0·19	0·04	...	...
S69	0·44	0·30	0·68	0·010	0·007	3·46	0·23	...	...
Q	0·28	0·21	0·57	0·025	0·039	0·99	1·32	0·38	...
X	0·28	0·15	1·12	0·010	0·026	0·82	0·67	0·205	...
MM	0·36	0·23	1·54	0·012	0·027	0·33	0·08	0·30	...
M20	0·21	0·08	0·60	0·042	0·064	...	...	...	...
N17	0·38	0·27	1·64	0·036	0·030	0·43	0·14	0·39	...
N19	0·45	0·28	0·54	0·030	0·020	0·24	1·07	0·23	...
N21	0·33	0·29	0·54	0·012	0·018	3·28	0·08	...	...
N22	0·36	0·31	0·56	0·013	0·013	3·28	0·16	...	...
N23	0·32	0·28	0·65	0·011	0·010	3·29	0·87	...	...
N23Mo	0·31	0·25	0·51	0·010	0·017	3·38	0·10	0·36	...
N31	1·01	0·32	0·42	0·019	0·010	...	1·34	...	...
N33	0·15	0·27	0·44	0·015	0·018	3·11	0·10	...	...
N37	0·10	0·21	0·29	0·010	0·013	4·82	0·06	...	...
N38	0·11	0·22	0·33	0·012	0·009	5·36	0·07	0·23	...
N100	0·34	0·24	1·32	0·028	0·033	0·87	0·47	0·17	...
DA	0·32	0·25	1·60	0·021	0·023	0·33	0·19	0·28	...
DB	0·41	0·20	0·75	0·014	0·025	0·19	0·93	0·22	...
DC	0·33	0·24	0·57	0·019	0·020	1·34	1·11	...	...
C10	0·20	0·85	0·70	0·029	0·024	3·98	1·45	0·54	...
C11	0·34	1·88	0·70	0·012	0·028	3·90	1·44	0·54	...
S65	0·29	0·22	0·45	0·031	0·028	2·98	1·34	0·34	...
A114	0·31	0·73	0·38	0·029	0·022	2·79	1·38	0·42	...
MC	0·43	0·20	0·68	...	...	0·15	0·08	...	...
FY	0·35	...	1·5	...	...	...	...	...	...

Specimen.

The size of specimen which had proved most convenient in previous work was a cylinder of 1¾-in. dia. by 2 in. long, and this size has been adopted as standard in the present work except where otherwise stated. It has been found that by soaking such specimens in hydrogen at 1100° C. for 24 hr., hydrogen contents of at least 6 c.c./100 g. can be obtained with most steels.

Soaking Furnace.

The furnace used for soaking two specimens at a time is wound over a length of 18 in. and the temperature is automatically controlled by a potentiometric regulator. The degree of reproducibility obtained in the soaking conditions is indicated by the fact that when four specimens of 3% chromium–molybdenum steel were treated individually in two different furnaces and water-quenched, the hydrogen contents, determined in the manner outlined below, were 7·65, 7·68, 7·77, and 7·79 c.c./100 g.

Isothermal Bath.

For temperatures between 150° and 450° C. an electrically heated salt bath was employed; for those in the region 450–750° C., an electrically heated lead bath was used. The salt bath contained 1 cwt. of a commercial salt melting at 135° C., and the lead bath 3 cwt. of lead. The total heat capacity of each bath was such that the rise in temperature on quenching two standard specimens from 1100° C. was not more than 10° C. By starting with the bath temperature slightly low, it was possible to ensure that after quenching the bath was within 5° C. of the required temperature.

Time in Isothermal Bath.

When a specimen of the standard size is quenched in lead or salt, some 4 or 5 min. must elapse before temperature conditions become steady. Since it was desired to know how much hydrogen was removed actually at the temperature of the isothermal bath, it was considered necessary to allow 10 min. for the attainment of steady temperature conditions before quenching the first specimen. Depending upon the transformation characteristics of the steel, a greater or lesser amount of hydrogen will be lost by both specimens during the first 10 min., and this accounts for the fluctuating values of "initial" hydrogen content observed in the experimental work.

Preliminary experiments showed that a peroid of 5 hr. in the isothermal bath at the optimum temperature was sufficient to reduce the hydrogen content to very low values, whilst leaving sufficient hydrogen under other conditions to bring out the effect of temperature upon the hydrogen removal. This time was adopted as standard for all experiments in which standard-sized specimens were used. It might have been thought advisable to leave the second specimen in the isothermal bath until a definite percentage of the austenite had transformed, but insufficient information was available concerning the isothermal transformation characteristics of the steels employed, particularly for large specimens with large grain-size and a high hydrogen content.

Determination of Hydrogen Content.

As a result of work described in a previous paper [1] it was found convenient to place freshly quenched specimens under paraffin, for the following reasons:

(1) Hydrogen determinations based on the vacuum-heating of freshly quenched specimens are liable to error, as a variable loss of gas is caused by removing the oxide scale from specimens immediately after quenching, when hydrogen evolution at room temperature is fairly rapid.

(2) Since the work is primarily concerned with hair-line crack formation, the experiments should be planned so that the susceptibility of each steel to crack formation under various conditions can be assessed; the specimen should therefore be kept at room temperature for a period sufficient for the cracks to develop. Experience had indicated that ageing for 1 week was adequate for specimens of standard size, and that at the end of that time the rate of hydrogen evolution at room temperature was generally small.

(3) Although facilities were improved later on, it was at first only possible to carry out one vacuum-heating determination of hydrogen at a time and, with the large number of specimens involved in this work, it proved useful to regard the paraffin tubes as a reservoir from which to draw specimens for hydrogen determinations as and when convenient.

After a week in paraffin the specimens were freed from surface oxide, washed thoroughly in acetone, and transferred to a vacuum furnace fitted with a differential oil-manometer. When the pressure indicated on a McLeod gauge was 0·001 mm. of mercury or better, the system was isolated from the Hyvac rotary oil-pump, and heating was commenced. The time taken to reach 650° C. was 1 hr., and a further period of 2 hr. was allowed at this temperature; the specimen was then allowed to cool down in the furnace. The amount of hydrogen evolved was calculated from the oil-manometer reading at room temperature and the analysis of a sample of gas extracted by means of a Töpler pump. The total hydrogen content of the specimen was given by the volume collected over paraffin plus the amount evolved on heating.

From time to time, specimens were reheated in the vacuum furnace to discover how much hydrogen was left after the first extraction. In all cases the figure was low; the following example may be regarded as typical. A specimen of the manganese–nickel–chromium–molybdenum steel, X, water-quenched after 24 hours' treatment in hydrogen at 1100° C., had a total hydrogen content of 6·46 c.c./100 g., of which 5·26 c.c./100 g. were evolved during the first vacuum heating. When a second extraction was carried out, the volume of gas was too small to allow a sample to be collected for analysis, but, assuming that the gas was 100% hydrogen, it would correspond to 0·06 c.c./100 g. On the basis of previous experience and the appearance of the discharge, it can be said that the actual hydrogen content of the gas evolved during the second extraction was certainly less than 50%, so that the hydrogen evolved on second extraction was probably less than 0·03 c.c./100 g.

The difference between the initial and final hydrogen contents, which gives the amount of hydrogen removed during isothermal treatment, was determined and expressed as a percentage of the initial content. This percentage has been regarded as a measure of the efficiency of hydrogen removal at the corresponding temperature.

After heating for hydrogen determination the specimens were sectioned transversely and examined for cracks by the magnetic crack detector and by etching with ammonium persulphate.

As a general rule the isothermal treatment was carried out at 50° C. intervals, from 150° to 750° C., inclusive, but closer intervals were employed where necessary. When it was required to investigate hydrogen removal at 850° and 1100° C., a slightly modified procedure was adopted. Treatment at 1100° C. was carried out in the soaking furnace, the hydrogen atmosphere being replaced by nitrogen as soon as the first specimen had been quenched. For work at 850° C. an electrically heated muffle was employed, and the two specimens were allowed to cool in air to 850° C. before one was quenched and the other placed in the muffle for 5 hours' treatment.

Nickel–Chromium–Molybdenum Steel, 4S11.

Only a small quantity of this steel was available and the investigation was confined to the temperature range 325–600° C., inclusive. The standard conditions were adhered to, except that the specimens were soaked for 45 hr. in hydrogen instead of the 24-hr. period adopted in later work. The results are given in Table II.

The hydrogen contents of the initial and the final specimens are plotted against the temperature of isothermal treatment in Fig. 1(a), and it will be seen that the final hydrogen content is at a minimum at 450° C. The initial content is not constant with temperature, probably owing to the loss of hydrogen during the first 10 min., whilst the specimens are attaining the temperature of the lead bath. This makes it desirable to measure the efficiency of hydrogen removal in terms of the initial hydrogen content, and this has been done

TABLE II.—*Isothermal Removal of Hydrogen from Ni–Cr–Mo Steel*, 4S11.

Temp. of Isothermal Treatment, ° C.	Initial Specimen (10 min. in bath).		Final Specimen (5 hr. in bath).		H_2 Removed during Treatment, %.
	H_2 Content, c.c./100 g.	Description of Cracks.	H_2 Content, c.c./100 g.	Description of Cracks.	
600	4·64	Radial.	4·28	Radial.	7·8
550	5·23	,,	3·48	,,	33·5
500	6·37	,,	2·59	No cracks.	59·3
450	4·67	Deep-seated random with a few radial.	0·59	,,	87·4
420	4·92	Deep-seated random.	0·78	,,	84·2
350	4·38	,, ,,	1·43	,,	67·4
325	4·29	,, ,,	1·46	,,	66·0

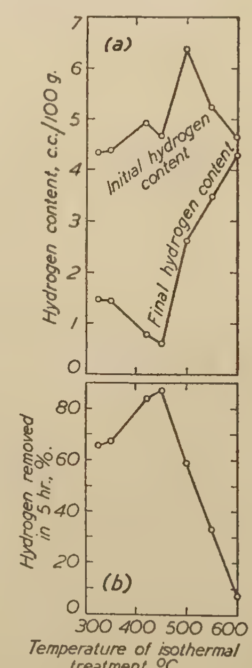


FIG. 1.—Isothermal Removal of Hydrogen from 4S11.

in Fig. 1(*b*), where the amount of hydrogen removed is expressed as a percentage of the initial content and plotted against the temperature of treatment.

It will be seen that the percentage of hydrogen removed rises from about 8% at 600° C. to approximately 87% at 450° C. As the temperature of treatment is further lowered, the efficiency of removal falls off, so that at 325° C. about 65% is removed. It is of interest that after treating at 450° C. for 10 min., the cracks observed in the specimen consisted of a mixture of radial and deep-seated random cracks. Below this temperature, only deep-seated, random cracks were observed, whereas above it the cracks were invariably radial. There was little difference in the number of cracks observed in the specimens treated at 600° C., and this is in keeping with the small difference between the hydrogen contents.

Nickel Steel, N22.

While awaiting further supplies of 1¾-in. dia. steel, it was decided to carry out experiments on a nickel steel, *N*22. This was available in 1¼-in. round bar, and specimens were machined to 1¼ in. dia. and 1¼ in. long. To allow for the smaller size of the specimens, they were removed from the isothermal bath after 5 min. and 2 hr., respectively. Apart from this, the standard treatment was followed throughout. The results are given in Table III.

TABLE III.—*Isothermal Removal of Hydrogen from Nickel Steel*, N22 (*Small Specimens*).

Temp. of Isothermal Treatment, ° C.	Initial Specimen (5 min. in bath). H_2 Content, c.c./100 g.	Final Specimen (2 hr. in bath). H_2 Content, c.c./100 g.	H_2 Removed during Treatment, %.
650	5·20	2·12	59·2
600	6·56	0·54	91·8
550	2·75	0·66	76·0
500	5·32	1·17	78·0
450	3·88	0·25	93·6
400	4·75	0·37	92·2
350	5·24	0·15	97·1
300	3·48	0·32	90·8
250	3·51	0·43	87·8
200	4·51	1·27	71·8
150	4·00	1·55	61·2

The hydrogen contents of the initial and final specimens are plotted against temperature of isothermal treatment in Fig. 2(*a*), and it will be seen that the final hydrogen contents are very low in the range 250–450° C. The percentage of hydrogen removed during the isothermal treatment is plotted against temperature in Fig. 2(*b*). In spite of the considerable fluctuations in initial hydrogen content, the shape of the curve in Fig. 2(*b*) is closely related to that of the final content curve of Fig. 2(*a*), with maximum hydrogen removal in Fig. 2(*b*) corresponding to minimum final content in Fig. 2(*a*). The salient features of Fig. 2(*b*) are (i) the high rate of removal at 600° C., (ii) the minimum in the curve at 550–500° C., (iii) the high rate of removal from 450° to 250° C., and (iv) the rapid falling-off in hydrogen removal below 250° C.

Specimens removed from the isothermal bath after 5 min. were sectioned, and examined for

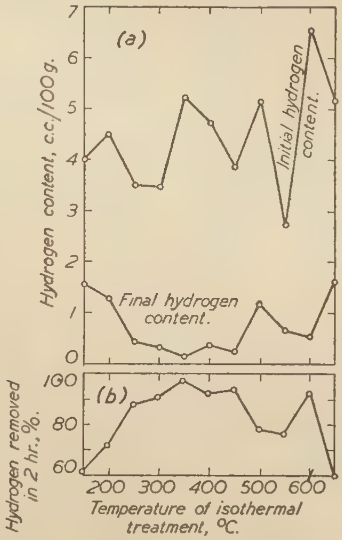


FIG. 2.—Isothermal Removal of Hydrogen from *N*22.

cracks. Those isothermally treated at 650° and 600° C. both showed many radial cracks, whilst the remainder of the specimens gave many "dots," which had the appearance of etching pits. The distribution of these dots suggested that they might have a similar origin to the cracks. Thus, in the specimen treated at 450° C., the dots were deep-seated and in random distribution, but in specimens treated at 350° C. and below, all the dots were confined to an annular space normally occupied by radial cracks. Intermediate distributions were observed in the specimens treated at 400°, 500°, and 550° C.

Manganese–Molybdenum Steel, FA.

The work carried out on this steel conformed to the standard conditions described above, except that the specimens were soaked for 45 hr. in hydrogen. The results obtained are given in Table IV.

Initial and final hydrogen contents are plotted against temperature of isothermal treatment in Fig. 3(*a*), and it will be seen that the final hydrogen contents are very low in the range 500–250° C. Typical etched sections of initial specimens are reproduced in Fig. 10. After these experiments

had been carried out it was suggested that hydrogen removal would be most effective at 625° C., at which temperature steel of this composition transforms readily. As no more steel of 2-in. dia. was available, it was decided to carry out supplementary experiments using specimens of $1\frac{1}{8}$-in. dia. and $1\frac{1}{8}$ in. long, as steel of this diameter was available from the same cast. The specimens were soaked in hydrogen in the normal way and given isothermal treatment at 600°, 625°, and 650° C. The initial specimens were removed from the bath after 5 min., and the final specimen after 2 hr. The results obtained are given in Table V., together with the corresponding values obtained on the standard specimens at 600° and 650° C.

Table IV.—*Isothermal Removal of Hydrogen from Mn–Mo Steel,* FA.

Temp. of Isothermal Treatment, ° C.	Initial Specimen (10 min. in bath).		Final Specimen (5 hr. in bath).		H_2 Removed during Treatment, %.
	H_2 Content, c.c./100 g.	Description of Cracks.	H_2 Content, c.c./100 g.	Description of Cracks.	
650	6·50	Radial.	1·12	No cracks.	82·8
600	5·35	,,	1·53	,,	71·4
550	3·85	,,	2·08	,,	46·0
500	5·83	Deep-seated, random.	0·50	,,	91·4
450	7·25	,, ,,	0·45	,,	93·8
400	5·82	,, ,,	0·47	,,	91·9
350	5·07	,, ,,	0·34	,,	93·3
300	6·31	Radial and random mixed.	0·38	,,	94·0
250	5·02	Radial.	0·33	,,	93·4
200	4·15	,,	0·85	,,	79·5
150	4·68	,,	1·37	,,	70·7

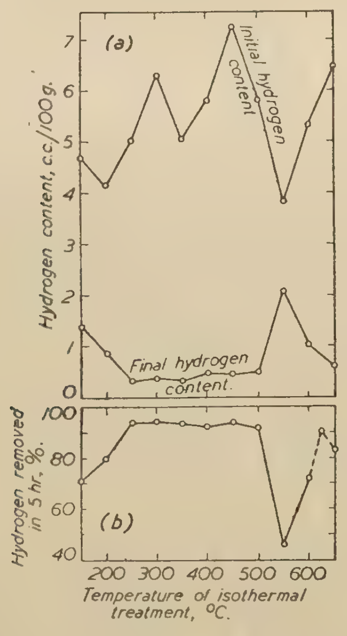


Fig. 3.—Isothermal Removal of Hydrogen from *FA*.

Whilst it is clear that hydrogen removal is a maximum at 625° C., it is not possible to decide with any certainty what percentage of the initial hydrogen content would have been removed at 625° C. if larger specimens had been available. The ratios between the percentage of hydrogen removed from large and small specimens are 1·14 and 1·05 at 650° and 600° C. respectively. Assuming each of these values in turn, the corresponding values of the percentage of initial hydrogen content likely to be removed at 625° C. from the large specimen were calculated and found to be 93·5 and 86·1% respectively. For the purpose of completing Fig. 3(*b*), showing the relation between percentage of hydrogen removed and temperature of isothermal treatment, the mean value of 90% was assumed. The exact value to be assigned to the percentage of hydrogen removed at 625° C. is not of great importance, since in the range 450–250° C. some 94% is removed, so that even if hydrogen removal at 625° C. were more effective than at 400° C. it could only be by a few per cent. Another point to be borne in mind in assessing these results is that the maximum in the intermediate region spreads over a temperature range of 250° C.

Table V.—*Isothermal Removal of Hydrogen from Mn–Mo Steel,* FA.

Temp. of Isothermal Treatment, ° C.	Hydrogen Content.	Small Specimen.	Large Specimen.
650	Initial.	5·91 c.c./100 g.	6·50 c.c./100 g.
	Final.	1·63 ,,	1·12 ,,
	Removed.	72·4%	82·8%
625	Initial.	4·76 c.c./100 g.	...
	Final.	0·86 ,,	...
	Removed.	82·0%	...
600	Initial.	7·48 c.c./100 g.	5·35 c.c./100 g.
	Final.	2·36 ,,	1·53 ,,
	Removed.	68·5%	71·5%

3% *Chromium–Molybdenum Steel*, CM.

The conditions which have been described as standard for isothermal work were observed in all respects for this steel. The results obtained are given in Table VI. 200° C., inclusive. A noteworthy feature of this steel is that the final hydrogen content is higher than in other steels examined, the minimum value recorded being 0·90 c.c./100 g., at a treatment temperature of 725° C.

TABLE VI.—*Isothermal Removal of Hydrogen from 3% Cr–Mo Steel*, CM.

Temp. of Isothermal Treatment, ° C.	Initial Specimen (10 min. in bath).		Final Specimen (5 hr. in bath).		H_2 Removed during Treatment, %.
	H_2 Content, c.c./100 g.	Description of Cracks.	H_2 Content, c.c./100 g.	Description of Cracks.	
800	6·12	Many fairly long radial cracks.	2·78	No cracks.	54·6
750	5·97		1·57		73·7
725	6·72		0·90		86·6
700	5·04		1·00		80·2
650	6·04		3·22		46·7
600	5·92		3·74	8 radial cracks, mixture of short and long.	36·8
550	6·40		4·65	19 ,, ,,	27·3
500	7·23	Very numerous shorter radial cracks.	5·11	26 ,, ,,	29·3
450	5·48	2 radial cracks.	2·12	No cracks.	61·3
400	6·03	No cracks.	1·55		74·3
350	6·11	,,	1·43		76·6
300	4·63	1 radial crack.	1·06		77·1
250	5·79	Relatively few radial cracks, most extending to the surface.	1·70		70·6
200	7·29		1·77		75·7
150	6·72		3·28		51·2

Initial and final hydrogen contents are plotted against temperature in Fig. 4(*a*), and the percentage of initial hydrogen removed during the isothermal treatment is similarly presented in Fig. 4(*b*). According to these results, hydrogen removal is most effective at 725° C., and there is a range of 200° C. centred about 550° C. in which removal is low, followed by a removal of from 70 to 80% at temperatures between 400° and

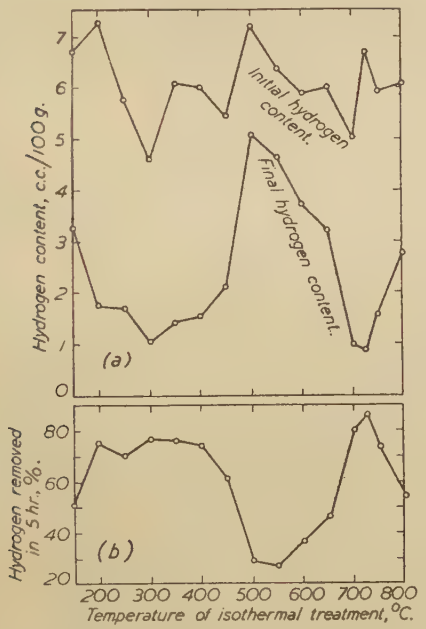


FIG. 4.—Isothermal Removal of Hydrogen from *CM*.

2% *Nickel–Vanadium Steel*, NV.

Using the standard conditions of experiment, the results reported in Table VII. and illustrated in Figs. 5(*a*) and 5(*b*) have been obtained with a 2% nickel–vanadium steel.

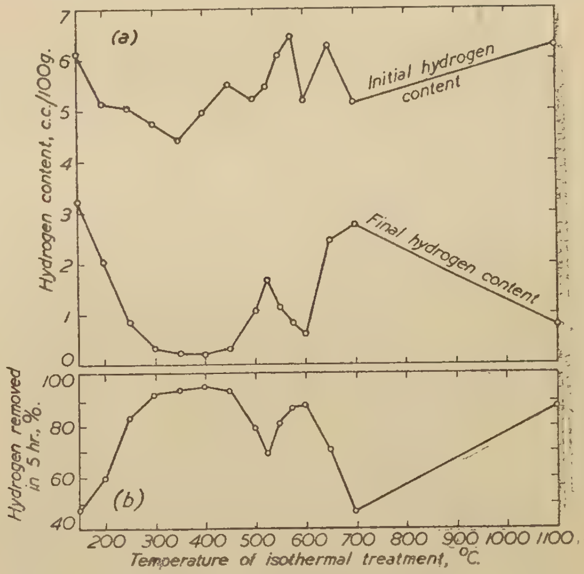


FIG. 5.—Isothermal Removal of Hydrogen from *NV*.

The shape of the curve showing the variation of hydrogen removal with temperature (*see* Fig. 5(*b*)) is almost identical with that reported for the 3½% nickel steel, *N*22, the noteworthy features being the high rate of removal between 250° and

TABLE VII.—*Isothermal Removal of Hydrogen from 2% Ni–V Steel,* NV.

Temp. of Isothermal Treatment, ° C.	Initial Specimen (10 min. in bath).		Final Specimen (5 hr. in bath).		H_2 Removed during Treatment, %.
	H_2 Content, c.c./100 g.	Description of Cracks.	H_2 Content, c.c./100 g.	Description of Cracks.	
1100	6·28	Many medium radial.	0·77	No cracks.	87·7
700	5·17	Many medium radial, some random around quenching crack.	2·75	Few radial cracks.	46·8
650	6·28	Many fine radial, some random around quenching crack.	2·45	Few radial and 1 or 2 random around quenching crack.	61·0
600	5·20		0·60	No cracks.	88·5
575	6·47	Many fine, long and medium radial cracks.	0·83	,,	87·2
550	6·09	3 quenching cracks, and mixture of short and medium radial cracks.	1·15	,,	81·1
525	5·48	Many medium to long, radial cracks. Some random near quenching crack.	1·67	Several fine, deep-seated random cracks.	69·5
500	5·24	No cracks, but many pits.	1·07	No cracks.	79·6
450	5·50	Many short radial, 1 deep-seated.	0·33	,,	94·0
400	4·97	Many short radial, and many deep-seated random.	0·22	,,	95·6
350	4·42	Many medium radial and many deep-seated random.	0·25	,,	94·3
300	4·75		0·35	,,	92·6
250	5·06	No definite cracks, but many pits.	0·85	,,	83·2
200	5·14	8 or 9 short radial cracks extending almost to surface.	2·06	,,	59·9
150	6·12	2 medium, 1 long, radial extending almost to surface.	3·22	1 quenching crack, 2 deep-seated short random cracks.	47·4

500° C. and in the neighbourhood of 600° C., and the less rapid removal near 550° C.

Nickel–Chromium–Molybdenum Steel, V30.

The removal of hydrogen from this steel has been investigated under standard conditions and the results are given in Table VIII., and illustrated in Figs. 6(*a*) and 6(*b*).

Two sets of hydrogen contents are given for a treatment temperature of 550° C. These were obtained in experiments separated by several weeks, and although the numerical values are different, the percentage of hydrogen removed during the 5-hr. treatment is 30% in each case.

The curve showing the percentage of hydrogen removed, given in Fig. 6(*b*), indicates that (i) the optimum temperature range for hydrogen removal is 250–450° C., (ii) at 550° C. only 30% of the initial hydrogen content is removed during the isothermal treatment, and (iii) as the temperature is increased from 550° to 750° C. the percentage removed increases in a fairly regular manner to 65%. The results at 850° and 1100° C. are not strictly comparable with those obtained at lower temperatures, since isothermal treatment was given in air or in nitrogen instead of in the lead bath. It is possible that the apparent reduction in efficiency of hydrogen removal between 750° and 850° C. is not a genuine effect and that it should be associated with the change in conditions of isothermal treatment.

0·6% *Carbon Steel,* K6.

For purposes of comparison, the removal of hydrogen from a 0·6% carbon, 0·7% manganese

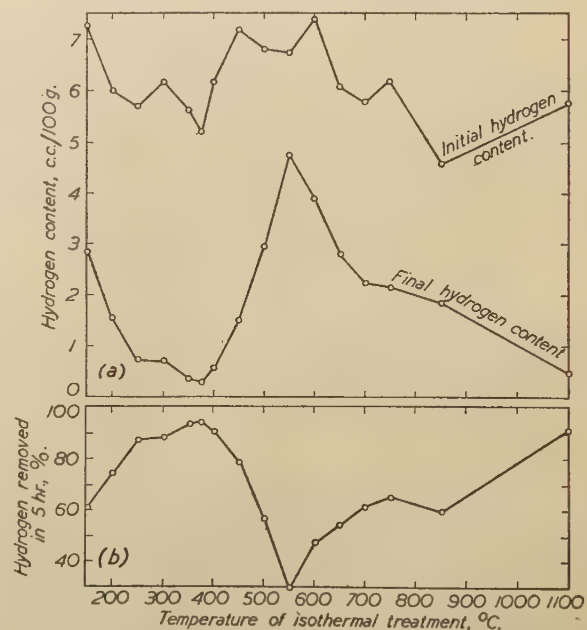


FIG. 6.—Isothermal Removal of Hydrogen from *V*30.

tyre-steel, *K*6, has been investigated, using standard conditions throughout. The results

TABLE VIII.—*Isothermal Removal of Hydrogen from Ni–Cr–Mo Steel,* V30.

Temp. of Isothermal Treatment, ° C.	Initial Specimen (10 min. in bath).		Final Specimen (5 hr. in bath).		H_2 Removed during Treatment, %.
	H_2 Content, c.c./100 g.	Description of Cracks.	H_2 Content, c.c./100 g.	Description of Cracks.	
1100	5·78	Many medium radial cracks with a few long ones.	0·47	No cracks.	91·9
850	4·59	Many radial fine cracks of medium length.	1·84	,,	59·9
750	6·21		2·15	4 long radial cracks, 2 extending to surface.	65·4
700	5·80	Many radial, very fine cracks, 2 extending to surface.	2·23	3 long radial cracks extending to surface.	61·6
650	6·09	Many radial, medium-length cracks.	2·79	1 radial crack extending to surface.	54·2
600	7·40	Many radial cracks, a few extending to surface.	3·89	7 radial cracks, 3 extending to surface.	47·4
550	6·00	Many radial, medium-length cracks.	4·22	About 25 fine, medium-length cracks, mostly radial, but some apparently random near severe quenching cracks.	29·7
550 *	6·76		4·74		29·9
500	6·83	Many radial cracks, a few near centre.	2·95	3 radial cracks.	56·8
450	7·19	4 long cracks, 2 radial and 2 deep-seated.	1·51	No cracks.	79·0
400	6·18	About 12 fine, medium-length cracks, random and deep-seated.	0·57	,,	90·8
375	5·21	Many short random, fine cracks.	0·29	,,	94·4
350	5·62	Numerous very fine and short cracks, randomly distributed throughout the specimen.	0·35	,,	93·8
300	6·18	Numerous very fine and short cracks, randomly distributed throughout the specimen.	0·71	,,	88·5
250	5·70	Many deep-seated medium-length cracks; 4 or 5 radial extending to surface.	0·72	,,	87·4
200	6·00	A number of radial cracks extending to surface, and many random, fine cracks.	1·54	1 radial crack extending to surface.	74·3
150	7·27	Many cracks, half radial and half random, but not deep-seated.	2·84	10 or more radial cracks extending to surface, 1 medium internal crack.	60·9

* Duplicate experiment.

obtained are given in Table IX., and illustrated in Figs. 7(*a*) and 7(*b*).

In general the initial hydrogen contents are low, but the fact that the specimen quenched from 1100° C. contained 8·80 c.c./100 g. shows that the soaking treatment has introduced a considerable quantity of hydrogen into the steel, although hydrogen is able to escape readily during the first 10 min. in the isothermal bath. Thus it would seem that in the case of the specimens treated at 550° C., some 5 c.c./100 g. were lost during this period.

At all temperatures below 700° C. the percentage of hydrogen removed is over 80%, and there is a tendency for the percentage removed to decrease as the temperature is lowered. The minimum rate of removal occurs at 750° C., but even here about 50% of the initial content is removed during isothermal treatment. From 750° C. upwards there is a general increase in the rate of removal as the temperature is increased, so that at 1100° C., the amount removed is about 93% and is comparable with the amount removed in the optimum temperature range of 700–600° C.

3½% *Nickel Steel,* S69.

Results obtained under standard conditions are reported in Table X., and illustrated in Figs. 8(*a*) and 8(*b*).

Etched sections of the initial specimens are reproduced in Fig. 11, and similar sections of the final specimens in Fig. 12.

Compared with some of the other steels examined, the initial hydrogen contents are reasonably constant, ranging from 5·01 to 6·27 c.c./100 g. Features of the curve showing percentage of hydrogen removed are (i) the high rate of removal between 250° and 450° C., (ii) the minimum rate

TABLE IX.—*Isothermal Removal of Hydrogen from 0·6% Carbon Steel,* K6.

Temp. of Isothermal Treatment, ° C.	Initial Specimen (10 min. in bath).		Final Specimen (5 hr. in bath).		H_2 Removed during Treatment, %.
	H_2 Content, c.c./100 g.	Description of Cracks.	H_2 Content, c.c./100 g.	Description of Cracks.	
1100	8·80	1 very severe quenching crack. Numerous medium and long radial cracks.	0·65	7 quenching cracks.	92·6
850	4·29	Many medium, 3 long radial cracks.	1·18	No cracks.	72·5
750	4·57	Very numerous, short and medium radial cracks.	2·36	6 deep-seated random cracks.	48·4
725	6·75	3 medium deep-seated and 30–40 medium radial cracks.	2·83	6 deep-seated random cracks.	58·1
700	5·03	25–30 medium and long radial cracks.	0·31	No cracks.	93·8
650	3·75	No cracks.	0·22	,,	94·1
600	4·60	,,	0·30	,,	93·5
550	3·51	,,	0·36	,,	89·7
500	4·60	1 fine long crack.	0·37	,,	92·0
475	4·79	3 medium long and 4 short to medium radial cracks.	0·56	,,	88·3
450	5·35	9 medium, radial cracks.	0·68	,,	87·3
425	7·64	Few short to medium and two fairly long, radial cracks.	1·15	,,	85·0
400	7·02	No cracks.	1·01	,,	85·6
350	6·21	,,	0·66	,,	89·4
300	4·92	,,	0·90	,,	81·7
250	5·21	,,	0·73	,,	86·0
200	5·33	,,	0·68	,,	87·2
150	6·27	,,	0·93	,,	85·2

TABLE X.—*Isothermal Removal of Hydrogen from 3½% Nickel Steel,* S69.

Temp. of Isothermal Treatment, ° C.	Initial Specimen (10 min. in bath).		Final Specimen (5 hr. in bath).		H_2 Removed during Treatment, %.
	H_2 Content, c.c./100 g.	Description of Cracks.	H_2 Content, c.c./100 g.	Description of Cracks.	
1100	6·03	Numerous fine, medium and long radial cracks.	0·33	No cracks.	94·6
850	5·21		1·46	,,	72·0
750	5·80	Numerous medium, radial cracks.	2·50	2 quenching cracks.	56·9
700	5·96	3 quenching, many small and medium radial internal cracks.	3·16	2 quenching cracks, 1 internal crack.	47·0
650	5·74	Numerous small, medium and long radial cracks.	3·01	2 severe quenching, 6 radial, and 3 deep-seated cracks.	47·6
600	5·82	3 quenching, 30 short radial cracks.	3·76	1 quenching, 7 radial, and about 25 deep-seated short to medium random cracks.	35·4
550	5·95	2 quenching, numerous radial, and 3 deep-seated cracks.	4·31	Many medium radial and about 30 deep-seated random cracks.	27·6
500	5·60	2 quenching, many radial, and 2 deep-seated cracks.	2·07	20–30 deep-seated random cracks.	63·0
450	5·22	20 deep-seated, random cracks.	0·57	No cracks.	89·1
400	5·01	Very numerous, very short random cracks.	0·88	,,	82·4
350	5·10	Few short radial near surface, and a few short deep-seated random cracks.	0·64	,,	87·5
300	5·58	2 quenching, 10 deep-seated random cracks.	0·90	,,	83·9
250	6·27	3 quenching and about 30 random cracks, some deep-seated.	1·42	,,	77·4
200	5·77	Very severe quenching cracks.	2·72	,,	52·9
150	6·11	No cracks.	3·25	,,	46·8
100	5·92	4 severe quenching cracks, many fine, small and medium cracks.	3·52	4 severe quenching cracks and 12 medium internal cracks.	40·5

of removal at 550° C., and (iii) the manner in which the rate of removal increases with temperature from 550° to 1100° C. For this steel and the conditions employed, the optimum temperature

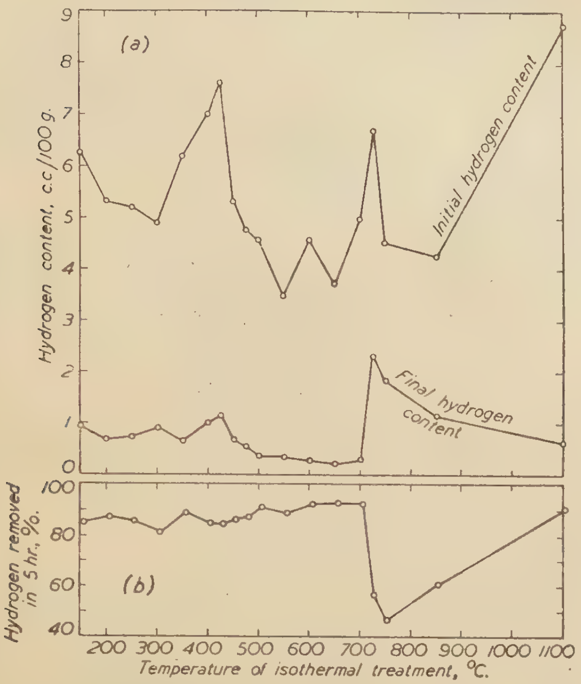


FIG. 7.—Isothermal Removal of Hydrogen from *K*6.

for the removal of hydrogen would appear to be 1100° C., at which temperature no less than 94·5% of the initial content was removed in 5 hr.

3% *Nickel Steel*, N33.

Results obtained for the case-hardening nickel steel *N*33 are reported in Table XI. and shown graphically in Figs. 9(*a*) and 9(*b*).

The initial hydrogen contents observed with steel *N*33 were low compared with most of the steels

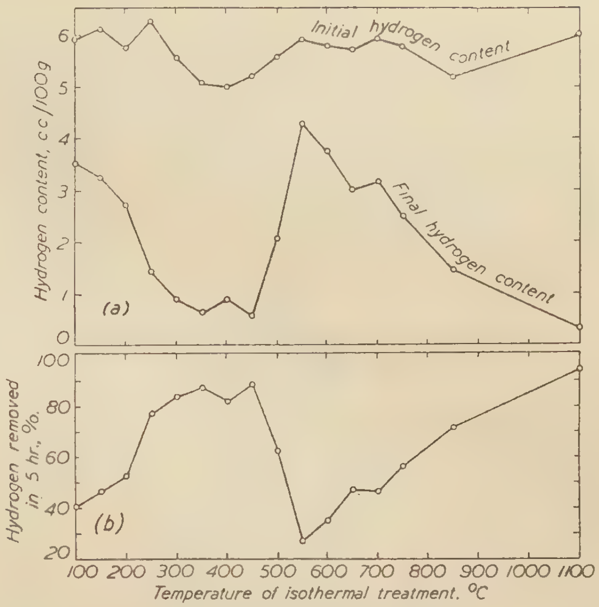


FIG. 8.—Isothermal Removal of Hydrogen from *S*69.

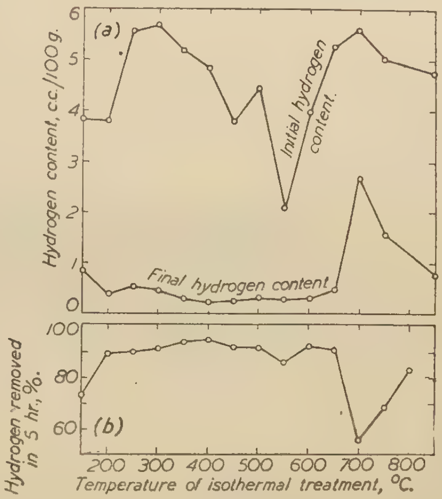


FIG. 9.—Isothermal Removal of Hydrogen from *N*33.

TABLE XI.—*Isothermal Removal of Hydrogen from* 3% *Nickel Steel*, N33.

Temp. of Isothermal Treatment, ° C.	Initial Specimen (10 min. in bath).		Final Specimen (5 hr. in bath).		H_2 Removed during Treatment, %.
	H_2 Content, c.c./100 g.	Description of Cracks.	H_2 Content, c.c./100 g.	Description of Cracks.	
850	4·72	None.	0·74	None.	84·2
750	5·01	1 medium internal radial crack.	1·53	,,	69·5
700	6·07	7 medium radial and 2 short, fine radial cracks.	2·65	,,	56·3
650	5·24	None.	0·44	,,	91·8
600	3·95	,,	0·28	,,	93·0
550	2·07	,,	0·27	,,	87·0
500	4·43	,,	0·31	,,	92·7
450	3·77	,,	0·26	,,	93·0
400	4·83	10 or more very fine random deep-seated cracks.	0·22	,,	95·4
350	5·17	1 very fine, small internal crack.	0·30	,,	94·4
300	5·67	None.	0·46	,,	91·9
250	5·55	,,	0·53	,,	90·5
200	3·80	,,	0·40	,,	89·6
150	3·82	,,	0·85	,,	73·3

examined, and very low in the neighbourhood of 550° C. From 650° to 200° C., the percentage of hydrogen removed during 5 hours' isothermal treatment is very high, being over 90% for most of this temperature range. The smallest percentage of hydrogen is removed at 700° C., but even in this case no less than 56% was removed in 5 hr. The hydrogen content of the final specimens was low in all cases except in the neighbourhood of 700° C.

The Law Governing the Removal of Hydrogen.

It was realized that if the results obtained relating the hydrogen removal to isothermal treatment were to be of wider application, it would be necessary to determine the law connecting hydrogen removal with time at a given temperature. In order to do this, the experimental procedure previously adopted would have to be modified so that several specimens could be soaked in hydrogen simultaneously and subsequently treated for different periods of time in the isothermal bath. A special furnace with three-zone temperature control was constructed so that, even in the absence of specimens, the temperature over a length of 12 in. was constant to within 10° at 1100° C. In use, five standard specimens were placed in the constant-temperature zone and soaked in hydrogen at 1100° C. for 24 hr. in the usual manner. All five specimens were then quenched in the salt or lead bath at the required temperature, and quenched in brine after suitable intervals. At 1100° C., the soaking furnace was also used for the isothermal treatment, but the hydrogen atmosphere was replaced by nitrogen as soon as the first specimen had been quenched. A laboratory electric muffle was used for work at 850° C., and the five specimens were cooled in air to this temperature before transferring to the muffle. Cooling from 1100° to 850° C. occupied not more than 2 min., but to ensure that a steady temperature had been reached, 10 min. in the muffle was allowed before the first specimen was quenched. This accounts for the slightly low initial hydrogen contents observed at 850° C., compared with those at 1100° C. The hydrogen contents of all specimens were determined in the normal manner.

It is convenient to divide the results into two groups according to whether transformation has, or has not, taken place during the period of isothermal treatment. On this basis, results obtained while the steel was entirely austenitic fall in the first group, and will now be dealt with in detail.

(a) *The Evolution of Hydrogen from Austenite.*

The detailed results obtained on steels examined in this group are given in Table XII.

Table XII.—*Law Governing Removal of Hydrogen—Group I.*

Time, hr.	H, Content, c.c./100 g.	Description of Cracks.
Ni–Cr–Mo Steel, V30, *at* 1100° *C. in Nitrogen* (*Fig.* 14).		
0·0	5·78	Many medium radial cracks, with a few long ones.
0·5	3·34	Fewer medium radial cracks; some long ones.
1·25	1·56	No cracks.
3·25	0·66	,,
5·0	0·47	,,
3½% *Nickel Steel*, S69, *at* 1100° *C., in Nitrogen* (*Fig.* 15).		
0·0	6·03	Numerous radial cracks.
0·5	3·38	Many radial cracks, but fewer than above.
1·0	2·06	2 quenching cracks.
2·5	0·79	3 quenching cracks.
5·0	0·33	No cracks.
3% *Cr–Mo Steel*, HD, (D.T.D. 306), *at* 1100° *C., in Nitrogen* (*Fig.* 16).		
0·0	7·70	Many medium, radial cracks.
0·5	3·82	11 long radial cracks.
1·25	1·91	7 long radial cracks.
3·5	0·64	No cracks.
5·0	0·50	,,
Low Ni–Cr–Mo Steel, Q, *at* 1100° *C., in Nitrogen* (*Fig.* 17).		
0·0	6·40	Many long and short radial cracks.
0·5	3·13	6 long and 3 short radial cracks.
1·0	2·23	4 long radial cracks.
2·0	1·13	2 quenching cracks.
5·0	0·58	No cracks.
Mn–Ni–Cr–Mo Steel, X, *at* 1100° *C., in Nitrogen* (*Fig.* 18).		
0·0	6·46	6 long and many short, fine, radial cracks.
0·5	3·22	5 long and many fine, radial cracks.
1·0	2·20	2 very long radial cracks.
2·0	1·21	Several very fine internal cracks.
5·0	0·56	No cracks.
3% *Cr–Mo Steel*, HD, (D.T.D. 306), *at* 850° *C., in Air* (*Fig.* 19).		
0·0	6·60	Numerous medium radial cracks.
0·5	4·21	Many medium radial cracks.
1·25	2·97	Some medium radial cracks.
3·0	1·73	One long radial crack.
5·0	1·14	No cracks.
Mn–Mo Steel, MM, *at* 625° *C., in Lead Bath* (*Fig.* 20).		
0·0	5·50	Numerous radial cracks.
0·5	4·84	Many radial cracks.
1·5	3·61	Many radial, but fewer than in previous specimen.
2·5	3·06	10 long and 2 short radial cracks.
5·0	2·14	No cracks.
Ni–Cr–Mo Steel, V30, *at* 550° *C., in Lead Bath* (*Fig.* 21).		
0·0	6·0	Quenching cracks, and many medium radial cracks.
0·33	5·77	Quenching cracks, but fewer.
1·0	5·14	Quenching cracks, still fewer.
2·5	4·99	12 medium radial cracks.
5·0	4·22	5 medium radial cracks.

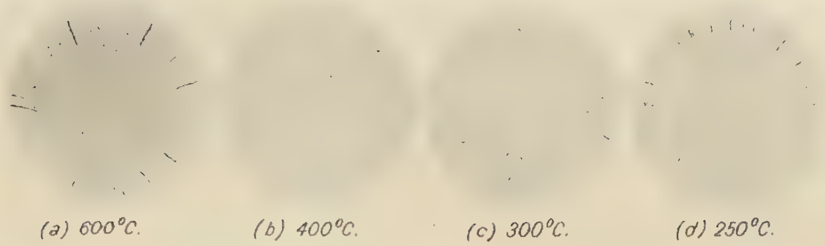


FIG. 10.—Steel *FA*. 10 min.

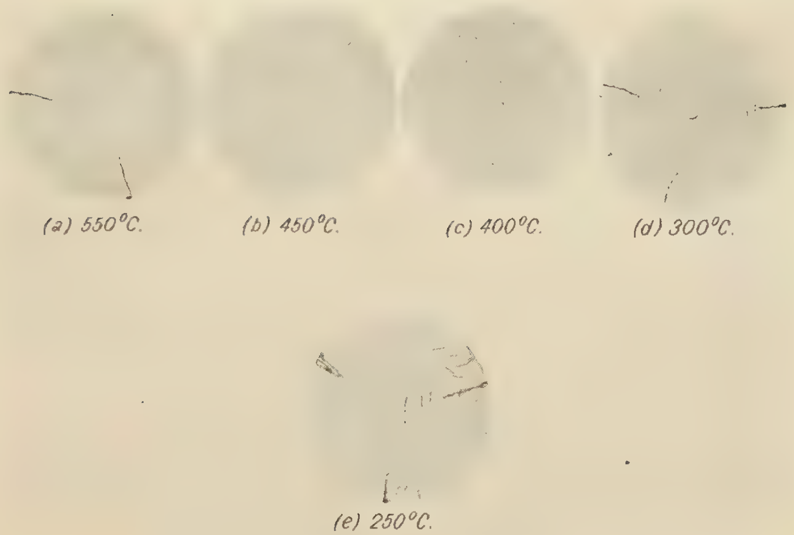


FIG. 11.—Steel *S*69. 10 min.

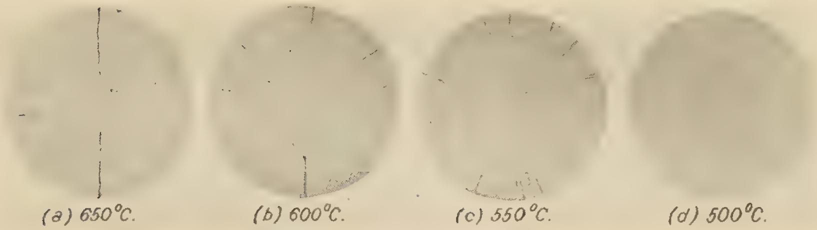


FIG. 12.—Steel *S*69. 5 hr.

FIGS. 10 to 12.—Cracks in Isothermally Treated Specimens. Four-fifths actual size.

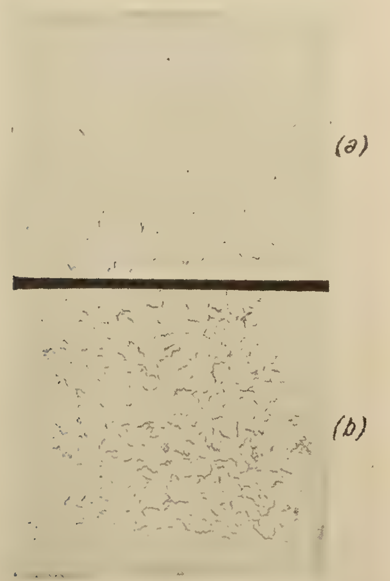


FIG. 13.—Steel 4*S*11, Hydrogen-Soaked and Water-Quenched from just below Ar_1 point.
(*a*) Sectioning begun before end of incubation.
(*b*) Sectioned after incubation had ended.

[*Andrew and others.*
[*To face p.* 78 P.

From the experimental results reported for the manganese–molybdenum steel, *FA*, it had been expected that 625° C. would likewise also correspond to the temperature of most rapid isothermal transformation of the steel *MM*. The high hydrogen content after 5 hr. at this temperature is not in keeping with that view, and even stronger evidence is available in the fact that the cracks observed after 2½ hr. at 625° C. were radial. It is our experience that radial cracks are associated with a martensitic structure and that, when transformation to pearlite or the intermediate structure

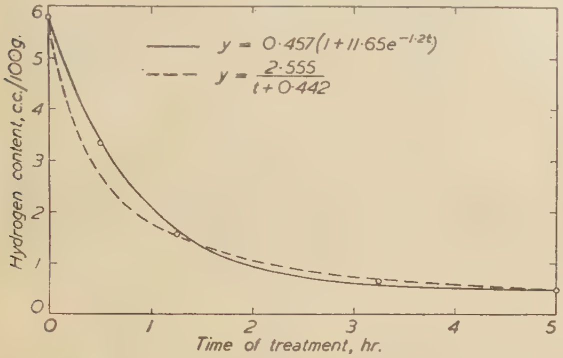


Fig. 14.—Isothermal Removal of Hydrogen from *V*30 at 1100° C.

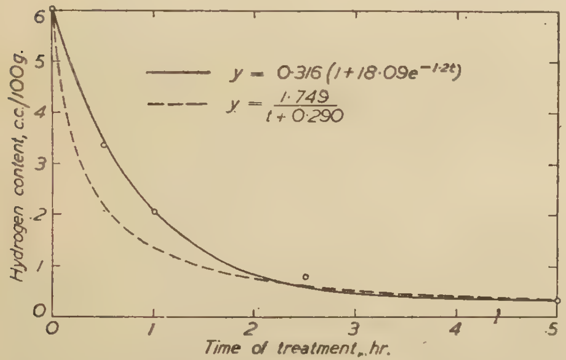


Fig. 15.—Isothermal Removal of Hydrogen from *S*69 at 1100° C.

occurs in the isothermal bath, any cracks formed are deep-seated and random.

It will be seen from Figs. 14 to 21 that in all cases the experimental results fall on smooth curves and that the rate of loss of hydrogen diminishes with time. This is to be expected and, in an attempt to find a mathematical expression which would fit the observed results, a simple exponential function of the type :

$$y = Ke^{-nt}$$

was used, where K is the initial hydrogen content, y the hydrogen content at time t, and n is a constant for a particular curve. It was found that when the constant n was calculated from the data for the initial and final specimens, the resulting curve did not agree with the experimental results for the intermediate times. It was then found that to a first approximation the experi-

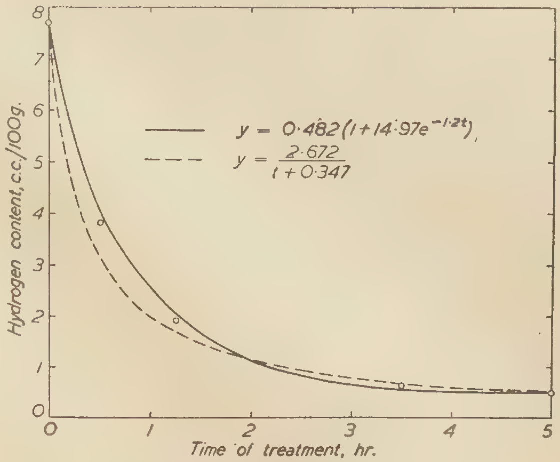


Fig. 16.—Isothermal Removal of Hydrogen from *HD* at 1100° C.

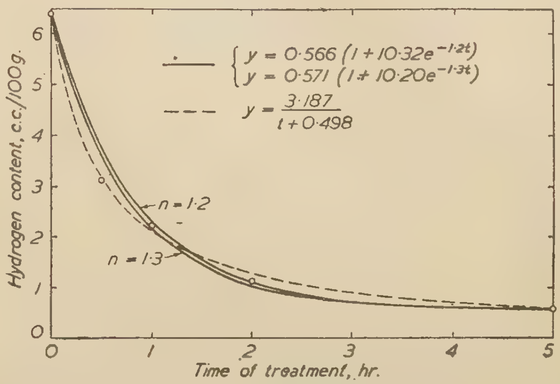


Fig. 17.—Isothermal Removal of Hydrogen from *Q* at 1100° C.

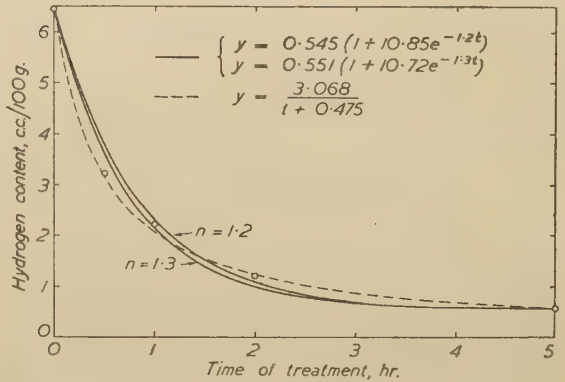


Fig. 18.—Isothermal Removal of Hydrogen from *X* at 1100° C.

mental curves were hyperbolæ and could be represented by :

$$y = Kc/(t + c)$$

where K, y, and t have the same significance as

before and c is a constant for the particular hyperbola. This expression was in excellent agreement with the curves shown in Figs. 19 (*HD*, 850° C.) and 20 (*MM*, 625° C.), and a reasonable fit was obtained in the case of Figs. 17 (*Q*, 1100° C.) and 21 (*V*30, 550° C.); but with Figs. 14, 15, and 16 the rate of hydrogen removal predicted by the hyperbola was too rapid in the initial stages. For convenience, in Figs. 14 to 21, the

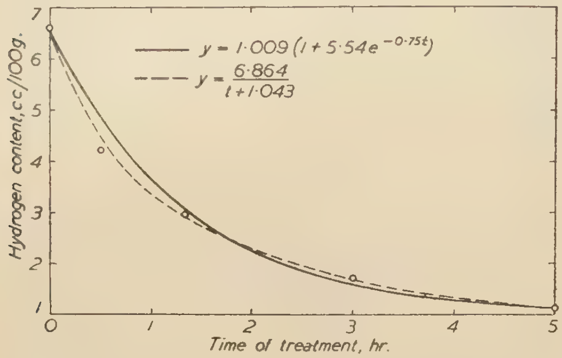


FIG. 19.—Isothermal Removal of Hydrogen from *HD* at 850° C.

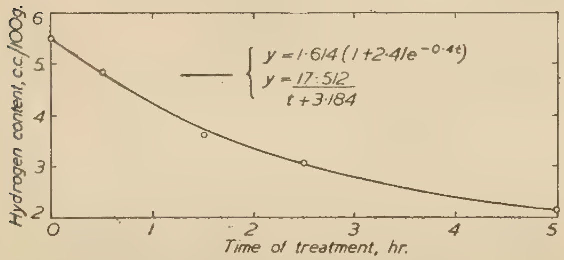


FIG. 20.—Isothermal Removal of Hydrogen from *MM* at 625° C.

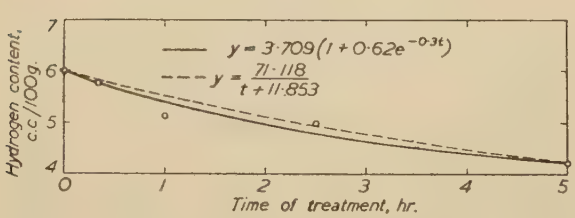


FIG. 21.—Isothermal Removal of Hydrogen from *V*30 at 550° C.

hyperbolæ calculated from the initial and final hydrogen contents are shown as broken lines.

Further investigation showed that a more satisfactory agreement with experimental results at 1100° C. was possible with the aid of the relationship:

$$y = K(1 + ae^{-t})/(1 + a)$$

where a is a constant for a given curve and can be determined from the initial and final hydrogen contents. At other temperatures, however, the agreement was not so good, and a further variable, n, was introduced to yield the formula:

$$y = K(1 + ae^{-nt})/(1 + a) \quad . \quad . \quad . \quad (1)$$

By suitably adjusting the value of n it was found that good agreement could be obtained at all temperatures in the austenitic range. The calculated curves for the hydrogen contents finally arrived at are plotted in Figs. 14 to 21, and it will be seen that the experimental points fall close to them.

When all the experimental curves had been treated in this manner, it was observed that the value of n appeared to be independent of the steel and to vary with the temperature of isothermal treatment. This is illustrated in Fig. 22, where a straight line has been drawn through the values of n.

The fact that equation (1) enables good agreement to be obtained with the experimental results over a wide range of temperature suggests that, although an empirical relationship,

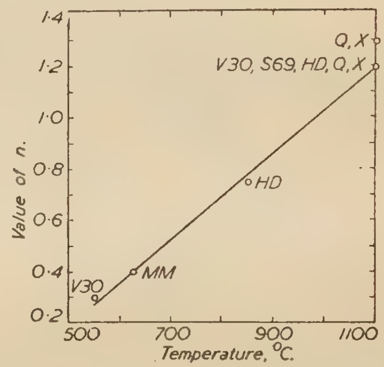


FIG. 22.—Variation of n with Temperature.

it may have a fundamental basis. Generally speaking, the more effective the isothermal treatment is in the removal of hydrogen the higher is the corresponding value of n, and when this is considered, together with the manner in which n varies with the temperature, it seems reasonable to suppose that n is closely related to the diffusion constant.

The function e^{-nt} has no significance unless nt is a pure number, and since the dimensions of the diffusion constant D are L^2T^{-1}, where L and T are the dimensions of length and time respectively, it follows that if n is proportional to D, the relationship must be of the form $n = kD/l^2$, where k is a constant and l is related to the linear dimensions of the specimen. The constant k would probably vary with the shape of the specimen, but should be constant for similarly shaped specimens of different mass.

When the experimental values of n were plotted in Fig. 22, it was found that the points were reasonably represented by a straight line.

On the other hand, it is well known that, in general, the value of the diffusion constant varies with the temperature according to the relationship :

$$D = Ae^{-b/T}$$

where A and b are constants and T is the temperature on the absolute scale. This equation may be rewritten to give :

$$\text{Log } D = \log A - b/T$$

from which it follows that a linear relationship exists between log D and the reciprocal of the absolute temperature. If the constant n is related to the diffusion constant in the manner outlined above, it should be possible to obtain a straight-line relationship corresponding to :

$$\text{Log } n = B - \text{constant}/T.$$

The values of log n are plotted against the reciprocals of the absolute temperature in Fig. 23, and it will be seen that the results can be fairly represented by a straight line with the equation :

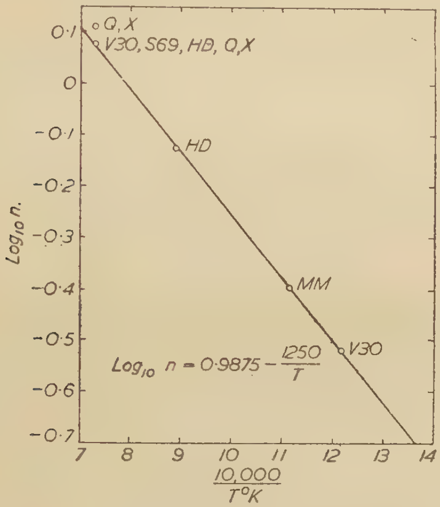


FIG. 23.—Relation between log n and Absolute Temperature.

$$\text{Log}_{10} n = 0{\cdot}9875 - 1250/T \quad . \quad . \quad . \quad (2)$$

If this equation is used to calculate the value of n at different temperatures, the curve illustrated in Fig. 24 results. When the experimental values of n are plotted on this curve, the agreement is extremely good. The only discrepancy occurs with the steels Q and X at 1100° C. In both cases an exact fit cannot be obtained with the empirical equation, but, as shown in Figs. 17 and 18, a reasonably good fit can be obtained with $n = 1{\cdot}2$ or $n = 1{\cdot}3$, and there is little to choose between these values.

It will be seen from Fig. 24 that the value of n is negligible below 100° C., and this is in keeping with the experimental observation that standard-sized specimens of 25% nickel steel and of commercially pure nickel which had been soaked in hydrogen at 1100° C. for 24 hr. and water-quenched, gave off no hydrogen at room temperature. Moreover, when the hydrogen-soaked austenitic steel was reheated in a vacuum furnace and the evolution curve recorded, it was found that there was no measurable evolution below 380° C., and that between 380° and 650° C. there was a progressive increase in the evolution of hydrogen. These observations are in good general agreement with Fig. 24 and are in strong contrast to the results obtained for low-alloy steels, in which the main peak on the evolution curve occurs below 400° C.

By once more applying the method of dimensions to equation (1) it may be shown that the constant a must be dimensionless. At the same time the results obtained at 1100° C. indicate that the value of a varies from steel to steel, although the same value of n applies to all at this temperature. Thus, values of a ranging from 10 to 20 were obtained at 1100° C. It will be noted that equation (1) indicates a lower limit to the hydrogen content of the steel at a given temperature, for as t approaches infinity, y becomes $K/(1 + a)$. It should be pointed out at this stage that the apparent lower limit to the hydrogen content may be a limitation imposed by the empirical equation, and it is possible that it has no physical significance. A general lower limit to the hydrogen content could be explained by (i) chemical binding between the hydrogen and the steel, or (ii) a partial pressure of hydrogen around the specimen throughout the isothermal treatment. At first sight it might appear that the second is the more likely explanation, but this would necessitate the value of a increasing with decreasing temperature, which is not in keeping with the experimental results. There is insufficient evidence to justify a more detailed discussion of the point at present.

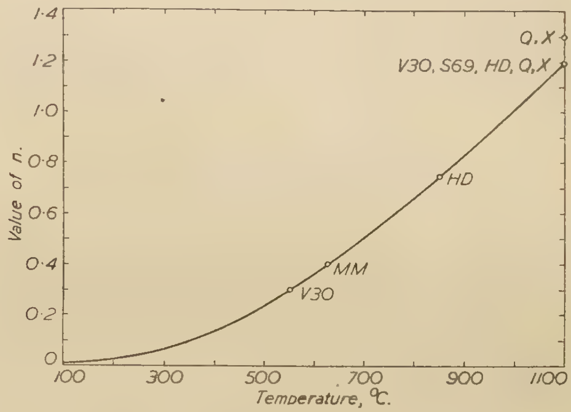


FIG. 24.—Relation between Calculated Values of n and Temperature.

The wide applicability of the empirical equation led to attempts to treat the problem mathematically. Barrer [2] has dealt with the problem of diffusion in the solid state under various conditions, but a general solution of the problem of loss of hydrogen from a cylinder of finite length cannot be given. It is clear that the process involves simultaneous loss of hydrogen from (i) the plane end surfaces and (ii) the cylindrical surface. Although it is not practicable to consider the two effects simultaneously in a mathematical treatment, each may be taken in turn.

Loss of Hydrogen from the Plane Ends.

In this case the cylinder may be regarded as an element of an infinite plate of thickness equal to the length of the cylinder. Under these conditions, diffusion will be unidirectional and Fick's law will apply, thus :

$$\frac{dc}{dt} = D\frac{d^2c}{dx^2}$$

where D is the diffusion constant, c is the concentration of hydrogen, and x and t refer to distance and time respectively. A solution of the equation is :

$$c = A_0 + A_1e^{-Dm_1^2t}\sin m_1x + A_2e^{-Dm_2^2t}\sin m_2x + \ldots A_ne^{-Dm_n^2t}\sin m_nx \quad . \quad (3)$$

where $A_0 \ldots\ldots A_n$ and $m_1 \ldots\ldots m_n$ are determined by the boundary conditions. The boundary conditions are that (i) when $t = 0$, $c = c_0$ from $x = 0$ to $x = L$ and (ii) when $t = \infty$, $c = c_L$ from $x = 0$ to $x = L$ where c_L is the limiting concentration determined by the experimental conditions.

When $t = \infty$, terms A_1 to A_n vanish, so that

$$c_L = A_0 \quad . \quad . \quad . \quad . \quad . \quad . \quad (4)$$

When $t = 0$:

$$c_0 - c_L = A_1 \sin m_1x + A_2 \sin m_2x + \ldots A_n \sin m_nx = f(x)$$

This function may be expressed as a half-range sine series of the form :

$$f(x) = b_1 \sin\frac{\pi x}{L} + b_2 \sin\frac{2\pi x}{L} + \ldots b_n \sin\frac{n\pi x}{L}$$

where

$$b_n = \frac{2}{L}\int_0^L f(x)\sin\frac{n\pi x}{L}\,.\,dx$$
$$= 4(c_0 - c_L)/n$$

for n odd and vanishes for n even.

Hence :

$$f(x) = \frac{4(c_0 - c_L)}{\pi}\left[\sin\frac{\pi x}{L} + \frac{1}{3}\sin\frac{3\pi x}{L} + \ldots \frac{1}{n}\sin\frac{n\pi x}{L}\right],$$

where n is odd.

Therefore :

$$c = c_L + \frac{4(c_0 - c_L)}{\pi}\left[e^{-\frac{D\pi^2t}{L^2}}\,.\sin\frac{\pi x}{L} + \frac{1}{3}e^{-\frac{9D\pi^2t}{L^2}}\,.\sin\frac{3\pi x}{L} + \ldots + \frac{1}{n}\,.e^{-\frac{n^2D\pi^2t}{L^2}}\,.\sin\frac{n\pi x}{L}\right]$$

where n is odd.

The concentration experimentally determined in this work at time t corresponds to the average concentration in the specimen from $x = 0$ to $x = L$. With a linear concentration gradient, this will be the concentration at $x = L/2$. On substituting this value and the corresponding values for c_0 and c_L we have :

$$y = y_L + \frac{4(K - y_L)}{\pi}\left[e^{-\frac{D\pi^2t}{L^2}} - \frac{1}{3}e^{-\frac{9D\pi^2t}{L^2}} + \frac{1}{5}e^{-\frac{25D\pi^2t}{L^2}} - \ldots + \frac{1}{n}e^{-\frac{n^2D\pi^2t}{L^2}}\right].$$

Putting $\frac{D\pi^2}{L^2} = N$, we have further that :

$$y = y_L + \frac{4(K - y_L)}{\pi}\left[e^{-Nt} - \frac{1}{3}e^{-9Nt} + \frac{1}{5}e^{-25Nt} - \ldots + \frac{1}{n}e^{-n^2Nt}\right] \quad . \quad (5)$$

When Nt is large, the second and higher terms of the exponential series become insignificant, and as a first approximation, therefore :

$$y = y_L\left[1 + \frac{4}{\pi}\left(\frac{K - y_L}{y_L}\right)e^{-Nt}\right] \quad . \quad . \quad (6)$$

In the consideration of the empirical equation (1) given above it was shown that the constant a of the empirical equation was given by $a = \frac{K - y_L}{y_L}$ and this leads to $y_L = \frac{K}{1 + a}$.

Substitution of these values in equation (6) gives :

$$y = \frac{K}{1 + a}\left[1 + \frac{4}{\pi}ae^{-Nt}\right] \quad . \quad . \quad . \quad (7)$$

Loss of Hydrogen from the Cylindrical Surface.

The law governing radial flow in a cylinder is :

$$\frac{dc}{dt} = D\frac{d^2c}{dx^2} - \frac{D}{x}\cdot\frac{dc}{dx}.$$

On substituting $c = ue^{-D\alpha^2t}$, this equation becomes :

$$\frac{d^2u}{dx^2} + \frac{1}{x}\cdot\frac{du}{dx} + \alpha^2u = 0$$

which is Bessel's equation of the first order, with solutions given by the appropriate Bessel functions, the choice of which is governed by the boundary conditions.

In the present case the boundary conditions are $c = c_L$ at $x = r$ for all values of t, and $c = c_0$ for $o < x < r$ and at $t = 0$, and the solution becomes :

$$c = c_L + \frac{2}{r}\sum_1^{\infty}\frac{1}{\alpha_n}\,.\,e^{-D\alpha_n^2t}\,.\,\frac{J_0(\alpha_nx)}{J'_0(\alpha_nr)}\cdot(c_L - c_0)$$

and the mean concentration $\bar{c}$ in the cylinder is given by :

$$\bar{c} = c_L - \frac{4(c_L - c_0)}{r^2} \sum \frac{1}{\alpha_n^2} \cdot e^{-D\alpha_n^2 t}$$

Using the notation previously adopted, this equation becomes :

$$y = y_L + \frac{4(K - y_L)}{r^2} \sum \frac{1}{\alpha_n^2} \cdot e^{-D\alpha_n^2 t}$$

In these equations, α_n is the nth root of the equation $J_0(\alpha_n r) = 0$, and the first four roots are :

$$\alpha_1 = \frac{2 \cdot 405}{r}; \ \alpha_2 = \frac{5 \cdot 520}{r}; \ \alpha_3 = \frac{8 \cdot 654}{r}; \ \alpha_4 = \frac{11 \cdot 792}{r}.$$

Substituting these values gives :

$$y = y_L + 4(K - y_L)\left[\frac{1}{5 \cdot 8} e^{-\frac{5 \cdot 8Dt}{r^2}} + \frac{1}{30 \cdot 5} e^{-\frac{30 \cdot 5Dt}{r^2}} + \frac{1}{75} e^{-\frac{75Dt}{r^2}} + \ldots\right] \quad . \quad (8)$$

The series within the brackets converges rapidly, and the second and higher terms can be neglected except when t is small. To a first approximation, therefore :

$$y = y_L + \frac{4(k - y_L)}{5 \cdot 8} \cdot e^{-\frac{5 \cdot 8Dt}{r^2}}.$$

This equation can be rewritten in the form :

$$y = \frac{K}{1 + a}\left(1 + \frac{4}{5 \cdot 8} ae^{-Mt}\right) \quad . \quad . \quad . \quad (9)$$

where $M = 5 \cdot 8D/r^2$.

Thus it will be seen that, for diffusion through the plane ends and also for radial diffusion, the equation relating hydrogen content with time can be expressed in the form :

$$y = \frac{K}{1 + a}(1 + abe^{-nt}) \quad . \quad . \quad . \quad (10)$$

In practice, diffusion is not confined to the radial and longitudinal directions, but it is reasonable to assume that the equation for the more complex diffusion process would nevertheless be of this form. It will be seen that equation (10) differs from the empirical equation (1), in that there is an additional constant, b, in the theoretical equation. For longitudinal diffusion, the value of b is $4/\pi = 1 \cdot 273$, whilst for radial diffusion the corresponding value is $4/5 \cdot 8 = 0 \cdot 69$. The value of b to apply in the practical case will clearly depend upon the proportions of the cylinder, but should lie between the limits 0·69 and 1·273. The experimental results obtained in this work indicate that for a length/diameter ratio of 8 : 7 the value of b does not differ greatly from unity. It will be remembered that the empirical equation found to fit the experimental results implied that for each temperature of treatment there was a lower limit to the hydrogen content, and therefore in both cases dealt with above a similar limiting value was deliberately imposed. However, the corresponding equations for the cases in which there is no lower limit can be obtained by substituting $y_L = 0$ in equations (5) and (8). This gives :

$$y = \frac{4K}{\pi}\left[e^{-Nt} - \frac{1}{3}e^{-9Nt} + \frac{1}{5}e^{-25Nt} - \ldots\right] \quad . \quad . \quad (5a)$$

$$y = 4K\left[\frac{1}{5 \cdot 8}e^{-\frac{5 \cdot 8Dt}{r^2}} + \frac{1}{30 \cdot 5}e^{-\frac{30 \cdot 5Dt}{r^2}} + \frac{1}{75}e^{-\frac{75Dt}{r^2}} + \ldots\right] \quad (8a)$$

For sufficiently large values of t these equations reduce to :

$$y = \frac{4K}{\pi} e^{-Nt} \quad . \quad . \quad . \quad . \quad (5b)$$

$$y = \frac{4K}{5 \cdot 8} e^{-Mt}. \quad . \quad . \quad . \quad . \quad (8b)$$

These are essentially of the same form as the exponential expression used in the first attempt to find the form of the experimental curve, and in all cases the agreement was very poor. It would seem, therefore, that the lower limiting value to the hydrogen content may have a real significance, although it is not possible to give a definite explanation at this stage.

(b) *Hydrogen Evolution from the Transformation Products of Austenite.*

So far, in dealing with the law governing hydrogen removal, it has been assumed that the steel has been in the austenitic condition throughout the isothermal treatment, and the remarks which have been made are correspondingly limited in their application. Some work has also been carried out at temperatures at which the steel would transform readily, and the results of the experiments carried out on steels in this group are given in Table XIII.

In the case of the 3% chromium–molybdenum steel, *HD*, the relationship between hydrogen content and time at 700° C. appears to be linear (*see* Fig. 29), but this will be dealt with in detail later. In Figs. 25 to 28 the experimental points are marked, and the curves correspond to the best fit possible with equation (1). For the steels *S*69 and *MM* at 400° C., the best value of n was 1·8, with the constant a having the values of 2·65 and 6·2 respectively. For the nickel–chromium–molybdenum steel, *V*30, at 375° C., the best fit was obtained with $n = 1 \cdot 2$ and $a = 17 \cdot 76$. The values of n seem to be very high, and the point arises that the transformation was occurring during the earlier stages of the experiment, so that the results do not strictly apply to the α state.

In an attempt to investigate the removal of hydrogen from the α state and to assess the value of a favourite commercial heat-treatment, the following experiment was carried out. Five standard specimens were soaked for 24 hr. in hydrogen

at 1100° C., and then quenched in a salt bath controlled at 300° C. After 13 min., the specimens were quickly transferred to the lead bath held at 640° C. The first specimen was quenched after 10 min., and the others after suitable

TABLE XIII.—*Law Governing Removal of Hydrogen—Group II.*

Time, hr.	H_2 Content, c.c./100 g.	Description of Cracks.
		3½% *Nickel Steel*, S69, *at* 400° *C. in Salt Bath.*
0·0	4·09	Many very short radial, and several deep-seated random cracks.
0·5	2·41	2 internal cracks.
1·0	1·51	No cracks.
2·5	1·24	„
5·0	1·12	„
		Mn–Mo Steel, MM, *at* 400° *C., in Salt Bath.*
0·0	5·40	Numerous radial cracks.
0·5	2·88	Many radial cracks.
1·5	0·93	Many radial, but fewer than in previous specimen.
3·0	0·75	10 long and 2 short radial cracks.
5·0	0·75	No cracks.
		Ni–Cr–Mo Steel, V30, *at* 375° *C., in Salt Bath.*
0·0	5·21	Many short random fine cracks.
0·33	3·96	Many short random fine cracks—more numerous but shorter.
1·0	1·87	Many short random fine cracks, but fewer.
2·5	0·43	No cracks.
5·0	0·29	„
		3½% *Nickel Steel*, S69 (*Quenched in Salt Bath at* 300° *C., held for* 13 *min., and Reheated to* 640° *C. in Lead Bath*).
0·0	2·36	No cracks.
0·5	1·46	„
1·0	0·64	„
2·0	0·36	„
5·0	0·15	„
		3% *Cr–Mo Steel*, HD, *at* 700° *C., in Lead Bath.*
0·0	5·83	Numerous, medium, radial cracks.
0·33	5·50	Similar, but fewer.
1·00	4·63	About 20 medium radial cracks.
2·5	3·39	No cracks.
5·0	0·99	„
		3% *Cr–Mo Steel*, HD, *at* 700° *C. in Lead Bath* (*Second Series*).
0·0	6·23	Many radial cracks.
2·0	3·70	1 short internal crack.
4·0	1·72	No cracks.
5·5	0·40	„

intervals of time up to 5 hr. Hydrogen contents were determined in the usual manner. The most striking feature of the results (*see* Table XIII.) is the extremely low value of 0·15 c.c./100 g. obtained for the final hydrogen content. This is the lowest value ever recorded during the course of this work and testifies to the efficiency of this type of preventive heat-treatment. The initial content of 2·36 c.c./100 g. is lower than

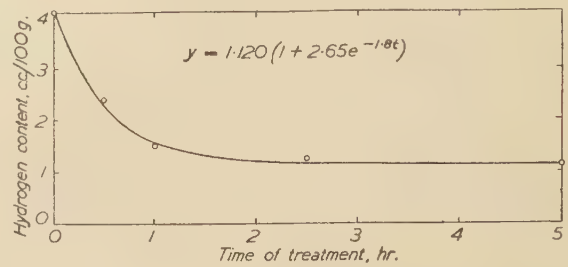


FIG. 25.—Isothermal Removal of Hydrogen from *S*69 at 400° C.

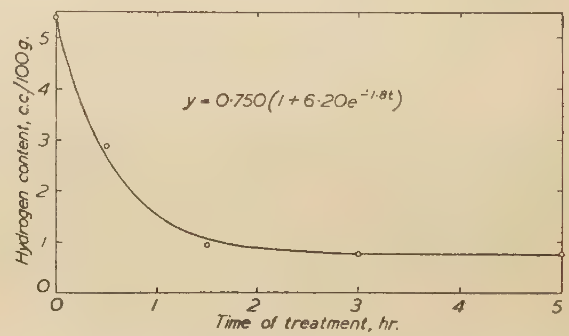


FIG. 26.—Isothermal Removal of Hydrogen from *MM* at 400° C.

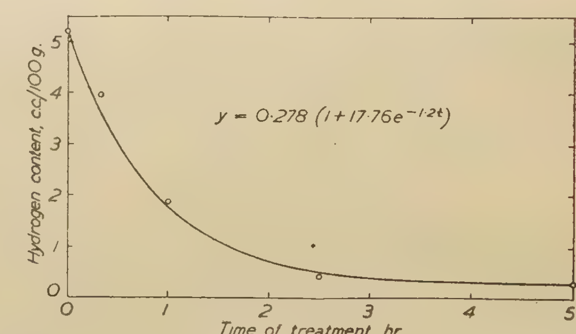


FIG. 27.—Isothermal Removal of Hydrogen from *V*30 at 375° C.

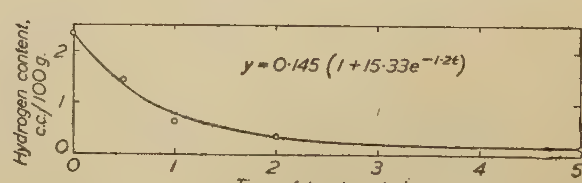


FIG. 28.—Removal of Hydrogen from *S*69, reheated at 640° C.

usual because of the losses occurring during the first 23 min. In Fig. 28 the curve corresponds to $n = 1{\cdot}2$ and $a = 15{\cdot}33$, and the agreement with the experimental points is good.

It was considered that for a steel of this composition, 13 minutes' isothermal treatment at 300° C. followed by reheating to 640° C. for 10 min. would be sufficient to ensure complete transformation, and this was supported by the low initial hydrogen content reported in Table XIII., for, if the steel had still been austenitic, far less hydrogen would have been lost during the heat-treatment. The value of $n = 1{\cdot}2$ may therefore be taken as applying to the α state at 640° C. and, when compared with the corresponding values obtained for the γ state, is certainly more probable than the values previously reported for steels *S*69 and *MM* at 400° C. and for *V*30 at 375° C.

Effect of Transformation upon Removal of Hydrogen from 3% *Chromium–Molybdenum Steel,* HD, *at* 700° *C.*—Having determined the effect of temperature upon the constant n in the γ region and obtained some idea of the most probable value of n at 640° C. for the α state, it is now possible to explain the hydrogen-content/temperature curve obtained for the 3% chromium–molybdenum steel, *HD*, at 700° C., provided that certain assumptions are made. These assumptions are: That the $\gamma \longrightarrow \alpha$ transformation proceeds in a known manner during the isothermal treatment and that the behaviour of austenite and its transformation products, when present side by side, can be adequately represented by the appropriate form of equation (1).

The results obtained for other steels in the austenitic condition justify the use of $n = 0{\cdot}5$ and a limiting content of the order of 2·8 c.c./100 g. for the γ state at 700° C. For the α state, the only reliable value of n is that of 1·2, obtained at 640° C. for reheated specimens. If the value of n increases with temperature in the manner observed for the austenitic condition, the most likely value of n for the transformation products at 700° C. would be 1·3. An arbitrary, though probable, value of 0·3 c.c./100 g. was used for the limiting hydrogen content in the α state, so that the relevant equations are:

$$y_{\gamma 700^\circ \mathrm{C.}} = 2{\cdot}8(1 + 1{\cdot}14e^{-0{\cdot}5t}) \quad . \quad . \quad (11)$$

$$y_{\alpha 700^\circ \mathrm{C.}} = 0{\cdot}3(1 + ae^{-1{\cdot}3t}) \quad . \quad . \quad . \quad (12)$$

The initial hydrogen content for the austenite was 6·0 c.c./100 g., as this was the mean of two experimental results given in Table XIII. The hydrogen content of the austenite at the moment of transformation was taken as the initial hydrogen content for the α state, which determines the value of a to be inserted in equation (12). It was also assumed that the transformation products ferrite and pearlite behaved in the same way as far as hydrogen removal was concerned.

Before the removal of hydrogen during transformation can be treated in a quantitative manner, it is necessary to know how the transformation proceeds, and sufficient direct evidence for this purpose was not available. A number of transformation/time relationships of the normal type were considered in turn, and it proved possible to give a satisfactory explanation of Fig. 29 with several of them. It was found that the gradually increasing rate of transformation in the initial stages, and the corresponding slowing-up of transformation towards completion, had little effect upon the final result; therefore the simplest case of a linear transformation/time relationship will be taken for purposes of illustration.

It was considered that a sufficiently good approximation would be obtained if the average hydrogen content of the specimen was calculated at ½-hr. intervals. Assuming that transformation commenced after ½ hr. in the lead bath, and was almost complete after 5 hr., some 11% of transformation products would be formed during each interval. Each 11% was dealt with as a

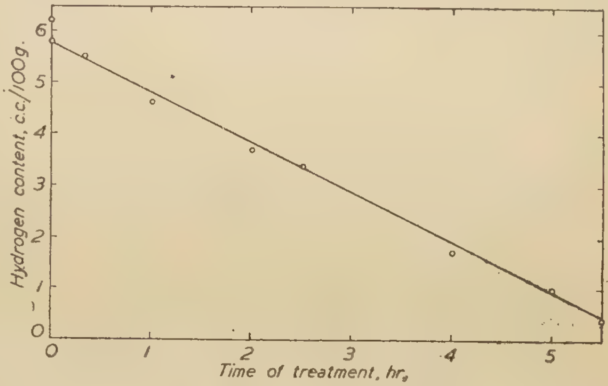


Fig. 29.—Isothermal Removal of Hydrogen from *HD* at 700° C.

separate portion having a different initial hydrogen content equal to that of the austenite at the moment of transformation. From the initial and limiting hydrogen contents, the appropriate value of a for insertion in equation (12) was calculated from the relationship:

$$a = \frac{\text{Initial hydrogen content}}{\text{Limiting hydrogen content}} - 1 \quad . \quad (13)$$

The residual austenite and the transformation products formed during each ½-hr. period were considered to behave independently throughout the experiment, so that the average hydrogen content of the specimen at any time could be obtained by simple proportion. The method of calculation should be clear from the results given in Table XIV., and the agreement between the calculated curve and the experimental points is shown in Fig. 30. For convenience, the curves calculated for the hydrogen removal from austenite and the decomposition products with initial content 6·0 c.c./100 g. at 700° C. and the

assumed transformation/time relationship are also reproduced in Fig. 30.

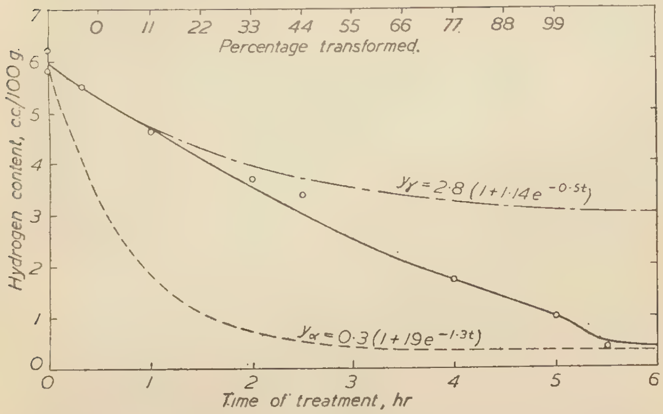


FIG. 30.—Effect of Transformation upon Isothermal Removal of Hydrogen from *HD* at 700° C. (Calculated curve.)

The experimental points show that the hydrogen removal is more rapid than would have been the case in the absence of transformation, and much slower in the initial stages than if the transformation had been complete before the experiment started. On the other hand, the hydrogen content after 6 hr. is so small that it could not have been much less if the steel had been in the α state throughout.

Effect of Specimen Size.—In the derivation of equation (1) it was shown that :

$$n = kD/l^2 \quad . \quad . \quad . \quad . \quad . \quad (14)$$

where l is related to the linear dimensions of the specimen, D is the diffusion constant, and the value of k is determined by the specimen shape. To test the validity of this relationship, experiments were carried out on the removal of hydrogen at 1100° C. from steel *S*69, using three different sizes of identically shaped specimens. Cylinders were used with a length/diameter ratio of 8 : 7, and they were machined from the same bar. The time of soaking in hydrogen at 1100° C. was the same in all cases, but the duration of the experiment to determine the law of hydrogen removal was adjusted to the size of the specimen, as shown in Table XV. Detailed results are given in Table XVI.

The experimental results are plotted in Fig. 31 together with the best-fit curves according to equation (1). The appropriate forms of this equation for the three different sizes of specimen are :

$$\text{Specimen } A : \ y = 0 \cdot 316 + 5 \cdot 72 e^{-1 \cdot 2t}$$

$$\text{Specimen } B : \ y = 0 \cdot 443 + 6 \cdot 85 e^{-2 \cdot 0t}$$

$$\text{Specimen } C : \ y = 0 \cdot 402 + 5 \cdot 64 e^{-4 \cdot 6t}$$

The value of $n = 1 \cdot 2$ for standard specimens at 1100° C. is based upon many experiments and can be taken as reliable. On this basis, the corresponding values of n for specimens B and C, calculated from equation (14) are 2·13 and 4·8 respectively. The difference between these values

TABLE XIV.—*Calculation of the Effect of Transformation upon the Removal of Hydrogen from 3% Cr–Mo Steel,* HD, *at 700° C.*

Time, hr.	H_2 Content of Austenite, c.c./100 g.	Austenite, %.	Transformation Products, %.	H_2 Content (c.c./100 g.) of the Different Batches of Decomposition Products Formed in the Times Shown.									Average H_2 Content of Specimen, c.c./100 g.
				½–1 hr.	1–1½ hr.	1½–2 hr.	2–2½ hr.	2½–3 hr.	3–3½ hr.	3½–4 hr.	4–4½ hr.	4½–5 hr.	
0·0	6·0	100	0	...	...	...	...	...	...	...	...	...	6·00
0·5	5·29	100	0	...	...	...	...	...	...	...	...	...	5·29
1·0	4·74	89	11	4·74	...	...	...	...	...	...	...	...	4·74
1·5	4·31	78	22	2·62	4·31	...	...	...	...	...	...	...	4·12
2·0	3·97	67	33	1·51	2·39	3·97	...	...	...	...	...	...	3·53
2·5	3·71	56	44	0·93	1·39	2·22	3·71	...	...	...	...	...	2·99
3·0	3·51	45	55	0·63	0·87	1·30	2·08	3·51	...	...	...	...	2·50
3·5	3·35	34	66	0·47	0·60	0·82	1·23	1·98	3·35	...	...	...	2·07
4·0	3·23	23	77	0·39	0·46	0·57	0·79	1·17	1·89	3·23	...	...	1·68
4·5	3·14	12	88	0·35	0·38	0·44	0·55	0·76	1·13	1·83	3·14	...	1·32
5·0	3·06	1	99	0·32	0·34	0·37	0·43	0·54	0·73	1·10	1·78	3·06	0·98
5·5	...	0	100	0·31	0·32	0·34	0·37	0·43	0·51	0·71	1·08	1·84	0·50
6·0	...	0	100	0·30	0·31	0·32	0·34	0·37	0·40	0·48	0·69	1·14	0·40
			Value of a	14·80	13·37	12·23	11·37	10·70	10·17	9·77	9·47	9·20	

TABLE XV.—*Adjustment of Time of Treatment According to Size of Specimen* (*Steel* S69).

Specimen	Dia., in.	Length, in.	Weight, g.	Duration of Experiment, hr.	Table No.
A . .	1¾	2	620	5	XII.
B . .	1 5/16	1½	260	3	XVI.
C . .	7/8	1	80	1¼	XVI.

and the experimental results of 2·0 and 4·6 respectively is therefore of the order of 5%; agreement is thus highly satisfactory, considering all the factors involved.

On the assumption that the relationship of

Table XVI.—*Removal of Hydrogen from 3½% Nickel Steel,* S69, *at* 1100° *C. in Nitrogen.*

Time, min.	H_2 Content, c.c./100 g.	Description of Cracks.
		Specimens $1\frac{5}{16}$ *in. dia.* × 1½ *in. long.*
0·0	7·29	Numerous short and long radial cracks.
30	2·78	6 long radial cracks and 1 quenching crack.
60	1·46	1 internal crack and 3 severe quenching cracks.
90	0·85	3 quenching cracks.
180	0·46	No cracks.
		Specimens ⅞ *in. dia.* × 1 *in. long.*
0·0	6·04	2 severe quenching cracks; many short and a few long radial cracks.
10	3·11	Several severe quenching cracks and about 12 medium radial cracks.
20	1·58	2 quenching cracks and 3 radial cracks.
40	0·65	2 quenching cracks and 1 radial crack.
60	0·46	2 quenching cracks.
75	0·42	No cracks.

equation (14) is of general applicability, it is possible to use the results of the work on the isothermal removal of hydrogen from standard specimens in the single-phase state to predict the

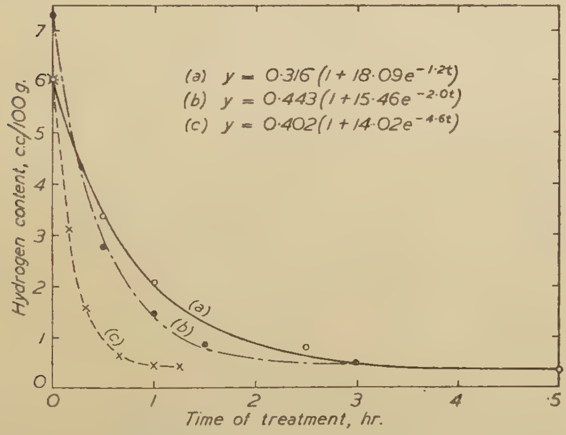


Fig. 31.—Effect of Specimen Size upon Isothermal Removal of Hydrogen from *S*69 at 1100° C.

times necessary for the removal of hydrogen from similarly shaped specimens of larger mass. For similarly shaped specimens at the same temperature, equation (14) gives:

$$\frac{n_1}{n_2} = \left(\frac{l_2}{l_1}\right)^2 \quad . \quad . \quad . \quad . \quad . \quad (15)$$

Given equal initial hydrogen contents in specimens of different mass, it follows from equation (1) that the final hydrogen contents will be the same for equal values of nt, that is, when $n_1t_1 = n_2t_2$. Combining this with equation (15) it will be seen that the effect of specimen size upon the time necessary for hydrogen removal to a given figure is given by:

$$t_2 = \left(\frac{l_2}{l_1}\right)^2 . t_1 \quad . \quad . \quad . \quad (16)$$

Thus, to take the case of the 3½% nickel steel, *S*69, at 1100° C., laboratory experiments with standard-sized specimens showed that 5 hr. were necessary to reduce the hydrogen content from 6·03 to 0·33 c.c./100 g. According to equation (16), the time necessary to bring about a similar reduction in the hydrogen content of a billet 25 in. in dia. and of corresponding length would be 1020 hr., or more than 6 weeks. To illustrate the effect of size still further, the hydrogen-content/

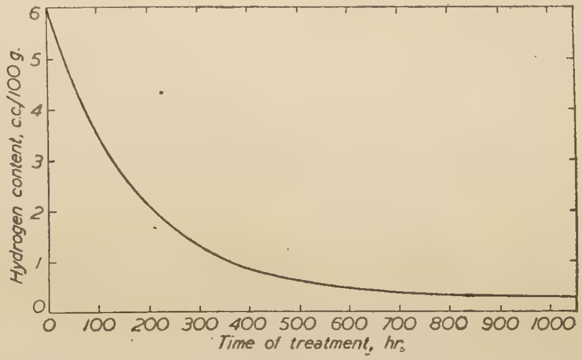


Fig. 32.—Isothermal Removal of Hydrogen from 25-in. dia. Billets of Steel *S*69 at 1100° C. (Calculated curve.)

time relationship at 1100° C. has been calculated for 25-in. dia. billets of *S*69 and is plotted in Fig. 32. It will be seen that no less than 9 days will be necessary to reduce the hydrogen content from 6·0 to 2·0 c.c./100 g. and that if a final content of less than 1·0 c.c./100 g. is required, a total time of 2½ weeks at 1100° C. will be necessary. The amount of hydrogen removed in the first 24 hr. is less than 1 c.c./100 g. and the rate of removal falls off with increasing time.

Since so many experimental results are available for different steels, showing the effect of 5 hours' isothermal treatment at various temperatures upon the hydrogen content, it may be useful to calculate how the time necessary to produce similar effects is determined by the size of the steel being treated. This has been done, and the results applicable to cylinders with a length/diameter ratio of 8 : 7, are shown in Fig. 33.

Effect of a Partial Hydrogen Atmosphere upon Hydrogen Removal.—The work so far carried out on the effect of heat-treatment upon hydrogen removal has corresponded to ideal conditions, in

that the specimen surface has been free from scale and the hydrogen evolved from the specimen has been continually swept away by a stream of nitrogen. Under industrial conditions there is the possibility of a small percentage of hydrogen being present in the heat-treatment atmosphere, and, with a view to investigating the possible effect of such small partial pressures of hydrogen upon hydrogen removal, the following experiments were carried out. Two similar specimens were soaked in hydrogen at 1100° C. for 24 hr., after which

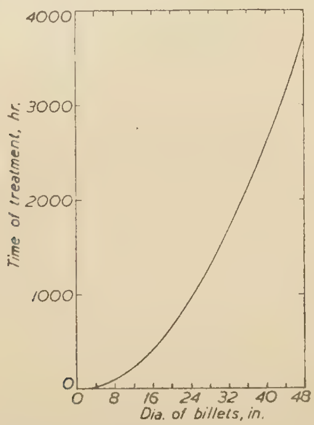


FIG. 33.—Effect of Billet Size upon Time Required for a Given Hydrogen Removal.

one was quenched in brine. The hydrogen content of this specimen was determined in the normal manner and was regarded as the initial hydrogen content. As soon as the first specimen was quenched, the atmosphere in the soaking furnace was changed to a mixture of hydrogen and nitrogen, accurately controlled by sensitive flow-meters, and the second specimen was contained in that atmosphere for 5 hr., after which it was quenched and analysed for hydrogen. Samples of the furnace atmosphere were collected at various times during the soaking period and the percentage of hydrogen determined. No appreciable variation in the analysis of the furnace atmosphere was detected. Typical analyses, taken at the beginning and end of one experiment, were:

	H_2, %.	CH_4, %.	CO_2, %.	CO, %.	O_2, %.	N_2, %.
11.50 A.M.	2·80	0·15	0·26	1·16	0·61	95·0
4.30 P.M.	2·88	0·55	0·30	0·96	0·23	95·0

With the 3% chromium–molybdenum steel *HD*,

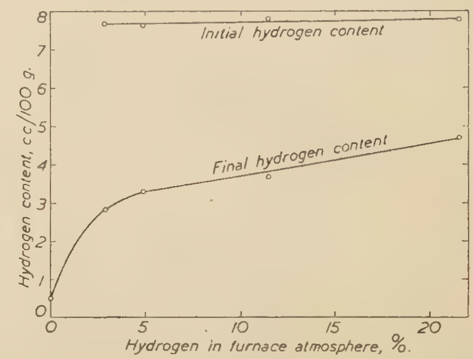


FIG. 34.—Effect of Partial Hydrogen Pressure in Furnace Atmosphere upon Hydrogen Removal from *HD* at 1100° C.

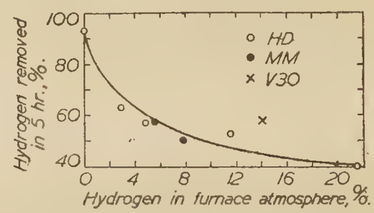


FIG. 35.—Effect of Partial Hydrogen Pressure in Furnace Atmosphere upon Hydrogen Removal from Steels at 1100° C.

the furnace atmosphere was varied within the range 0–25% of hydrogen. Isolated experiments were also carried out on the nickel–chromium–molybdenum steel, *V*30, and the 1½% manganese–

TABLE XVII.—*Effect of Furnace Atmosphere upon Hydrogen Removal.*

Steel.	Composition of Atmosphere.			"Initial" H_2, c.c./100 g.	Specimen Exposed to Furnace Atmosphere for 5 hr.	
	H_2, %.	CH_4, %.	Total H_2, %.		H_2 Content, c.c./100 g.	Description of Cracks.
3% Cr–Mo, *HD*.	0	0	0	...	0·50	No cracks.
	2·88	0·55	3·98	7·65	2·83	8 long radial cracks.
	4·87	0·25	5·37	7·68	3·32	14 medium-long radial cracks.
	11·50	0·33	12·20	7·79	3·70	7 long and 2 short radial cracks.
	21·50	1·14	23·80	7·77	4·69	2 long quenching cracks; 9 medium radial cracks.
Ni–Cr–Mo, *V*30.	0	0	0	5·78	0·47	No cracks.
	14·10	1·21	16·60	5·96	2·50	3 radial cracks.
1½% Mn–Mo, *MM*.	0	0	0	8·33	0·48	No cracks.
	5·60	0·70	7·00	6·48	2·76	1 severe quenching crack.
	7·85	0·84	9·53	6·89	3·43	6 long radial cracks.

molybdenum steel, *MM*. The results of these experiments are given in Table XVII. and graphically in Figs. 34 and 35.

The initial hydrogen contents of the *HD* specimens are remarkably constant and when the final hydrogen contents of the specimens are plotted against the hydrogen content of the furnace atmosphere, a smooth curve results (Fig. 34). By plotting the percentage of hydrogen removed from the steel against the hydrogen content of the furnace atmosphere, it is possible to draw a single curve to represent the results for all three steels (Fig. 35). From these curves it is clear that the first 2 or 3% of hydrogen in the furnace atmosphere are most effective in retarding hydrogen removal from the steel, and this is borne out by the observation of cracks in the corresponding specimens, although no cracks were observed when a pure nitrogen atmosphere was used.

It was to be expected that the effect of partial hydrogen pressures upon the removal of hydrogen would be less pronounced at lower temperatures, where the dissociation of molecular hydrogen on the steel surface would be less; to test this view experiments were carried out with the 1½% manganese–molybdenum steel *MM* at 650° C. Two standard-sized specimens of this steel were soaked together in hydrogen at 1100° C. for 24 hr. Both were then removed from the furnace, cooled in air to 650° C., after which one was quenched in water and the other transferred to another furnace controlled at 650° C. and fed with a hydrogen atmosphere. After 5 hr. in this furnace the second specimen was quenched and the hydrogen content determined in the normal manner. A control experiment was carried out in which nitrogen was used in place of hydrogen for heat-treatment at 650° C. The results obtained are given in Table XVIII.

TABLE XVIII.—*Effect of Furnace Atmosphere on Hydrogen Removal from Mn–Mo Steel,* MM, *at 650° C.*

Furnace Atmosphere.	Initial H_2 Content, c.c./100 g.	Specimen Exposed to Furnace Atmosphere for 5 hr.	
		H_2 Content, c.c./100 g.	Description of Cracks.
Nitrogen .	6·20	3·08	No cracks.
Hydrogen .	5·81	3·87	One quenching crack and two internal cracks.

Although more hydrogen has been removed from the specimen treated in nitrogen than from the one treated in hydrogen, the effect is much less marked than at 1100° C. Since an atmosphere of pure hydrogen has relatively such a small effect upon the rate of removal at 650° C., it seems unlikely that the effect of a few per cent of hydrogen in the furnace atmosphere will be pronounced.

Effect of Scale upon Removal of Hydrogen, at 1100° C.—An isolated experiment was carried out in an attempt to determine whether the presence of scale on the specimen surface was prejudicial to the removal of hydrogen. Two specimens of 3½% nickel steel, *S*69, were soaked in hydrogen at 1100° C. for 24 hr., after which one specimen was quenched to act as control. The furnace atmosphere was replaced by oxygen for 20 min., in order to build up a relatively thick layer of oxide on the second specimen as quickly as possible. For the remainder of the 5-hr. heat-treatment at 1100° C., a current of air was passed over the specimen, which was then quenched and the hydrogen content determined in the usual manner. During quenching the scale flaked off, and its thickness was found to be 0·012 in. The initial hydrogen content of the control specimen was found to be 6·88 c.c./100 g., while the scaled specimen contained 0·82 c.c./100 g., which corresponds to the removal of 88% of the initial hydrogen content during the 5-hr. heat-treatment at 1100° C. The results for the unscaled specimens of this steel have been given in Table X. from which it will be seen that the initial and final hydrogen contents were 6·03 and 0·33 c.c./100 g., respectively, corresponding to a removal of 94·6% in 5 hr. Owing to the difference between the initial hydrogen contents of the specimens, it is difficult to gauge the effect of the scale upon hydrogen removal. However, the law for the removal of hydrogen from *S*69 at 1100° C. has been determined, and the results for an initial content of 6·03 c.c./100 g. are reported graphically in Fig. 15. Similarly, the curve for the 3% chromium–molybdenum steel, *HD*, with an initial content of 7·70 c.c./100 g. is given in Fig. 16, and for both curves the value of n to be inserted in equation (1) is 1·2. It seems reasonable to suppose that the curve for *S*69, with an initial content of 6·88 c.c./100 g., will lie between those given in Figs. 15 and 16, in which case it can be said that, in the absence of scale, the hydrogen content would have been reduced to 0·82 c.c./100 g. in about 2½–3 hr., instead of the 5 hr. determined experimentally. Bearing in mind that the scale was of minimum thickness when the hydrogen content of the specimen was at a maximum and that even at the end of the experiment the scale was still only 0·012 in. thick, there does seem to be evidence in these results that the effect of scale on the outside of the specimen is to retard the removal of hydrogen. Further experimental work is necessary before a more definite statement can be made.

Miscellaneous Experiments.

Diffusion of Hydrogen through Steel.

In the early stages of this work it was considered desirable to compare the diffusion characteristics of different steels under similar conditions, particularly in the transformation range. Complications arise if the conventional type of diffusion apparatus is employed for steel specimens. Thus, reaction between carbon and oxygen causes the evolution of carbon monoxide and the differing oxygen and carbon contents makes comparison between different steels almost impossible. Furthermore, the diffusion of hydrogen is accompanied by some methane formation and, since both processes cause decarburization, it is not possible to obtain steady conditions until the steel is almost free from carbon. Since it was believed that the presence of carbon was likely to have a marked influence upon the diffusion of hydrogen through the steel, it was decided to use a form of specimen in which these effects would be reduced to a minimum, and the apparatus illustrated in Fig. 36 was developed for this investigation.

The specimen was $1\frac{3}{4}$ in. in dia. and 7 in. long, and a hole $\frac{1}{4}$ in. in dia. was drilled axially from one end to a depth of $5\frac{1}{2}$ in. The same end was tapered for a distance of $1\frac{1}{2}$ in., so that the parallel portion was $5\frac{1}{2}$ in. long. A mild-steel tube, of $\frac{1}{4}$ in. external dia. and $\frac{3}{32}$ in. bore, was passed down the centre of the specimen and an arc-welded joint was made between the two. A gas pressure of 150 atm. was maintained inside the tube whilst the specimen was under water and, if no bubbles could be detected, the specimen was then connected to a vacuum system fitted with sensitive gauges. No specimen was employed unless the known limiting vacuum of the system could be reached when the specimen was included in it.

During the experiment the specimen was surrounded by hydrogen, and the steel tube was connected to a sensitive differential oil-manometer and to a Hyvac pump. The normal procedure, adopted after a number of preliminary experiments, was to soak the specimen at 1050° C. at the same time maintaining a vacuum within it, until the evolution of carbon monoxide, as indicated on the discharge tube, was reduced to very small proportions. A period of 1–4 days was necessary for this, depending upon the steel from which the specimen was made. When this state had been reached, the system was isolated from the vacuum pump and the change in pressure during a given interval of time, usually 10 min. was measured on the oil manometer. This process was repeated at intervals until consistent readings were obtained. The temperature was then lowered by 100° C., and 24 hr. were allowed for equilibrium to be reached, during which time the interior of the specimen was evacuated and the furnace temperature controlled. The rate of change of pressure was then measured in the manner already described and the process repeated at successively lower temperatures, readings being taken at closer intervals within the transformation range. At temperatures below 300° C. the rate of change of pressure registered by the oil manometer was very small, and the temperature was then raised in stages. Readings of the rate of change in pressure were taken at suitable temperature intervals, and the results obtained on cooling

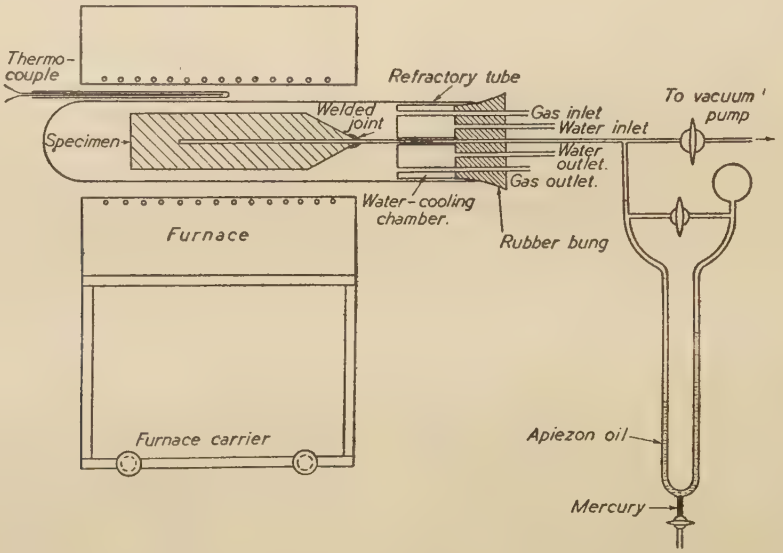


Fig. 36.—Apparatus for the Measurement of Diffusion or Evolution of Hydrogen from Steel.

and on heating were plotted on a single graph. Specimens were examined separately, and great care was taken to ensure that conditions were identical for the different steels.

The results obtained for the nickel–chromium–molybdenum steel, 4S11, the $1\frac{1}{2}$% manganese–molybdenum steel, *FA*, a mild steel containing 0·21% of carbon, *M*20 and an ingot iron are given in Fig. 37.

It should be emphasized that no attempt was made to carry out quantitative measurements of the diffusion constant; indeed, it is clear that, with the arrangement illustrated in Fig. 36, it is not possible to assign a definite temperature to any the readings taken. Unless a suitable temperature gradient is maintained along the specimen, the amount of hydrogen diffusing through the steel tube, the weld, and the conical section of the specimen will be large compared with that diffusing through the parallel portion. To overcome this, the furnace was deliberately wound in such a manner that the temperature of the weld was always well below that of the bulk of the specimen. The temperatures indicated in Fig. 37 were those registered by a thermocouple outside the refractory soaking tube, the junction being about 2 in. from the plane end of the specimen. From the results obtained in the transformation range it would appear that the temperatures indicated in Fig. 37 are approximately 30–50° C. too high on heating, and correspondingly too low on cooling.

The results illustrated in Fig. 37 show that for a given temperature the rate of diffusion, as measured by the rate of change of reading of the oil manometer, is higher when the steel is in the α than in the γ state. As would be expected, the heating and cooling curves agree above the Ac_1 change-point, and the extent of the hysteresis loop between the curves for cooling and heating respectively is closely related to the transformation characteristics of the steel. Thus, with the nickel–chromium–molybdenum steel, 4S11, the transformation on cooling is extremely sluggish and there is no sudden change in the diffusion rate. With the manganese–molybdenum steel, *FA*, transformation is complete within 24 hr. at about 600° C., and there is an abrupt increase in the amount of hydrogen diffusing into the specimen. With the mild steel, *M*20, the hysteresis loop was more limited; for the ingot iron the change was almost instantaneous. In general, the same curve applied to all four specimens in the α condition, and, with the exception of the mild steel, *M*20, another curve was common to the γ state. This curve even applied to *M*20 in the higher temperature range (950–1050° C.) and the deviation from the curve below 950° C. may be attributed to the presence of free ferrite in the specimen. The following experiment was carried out with the mild-steel specimen to obtain some idea of the speed with which hydrogen could diffuse through the steel. The hydrogen atmosphere was replaced by nitrogen, and the specimen

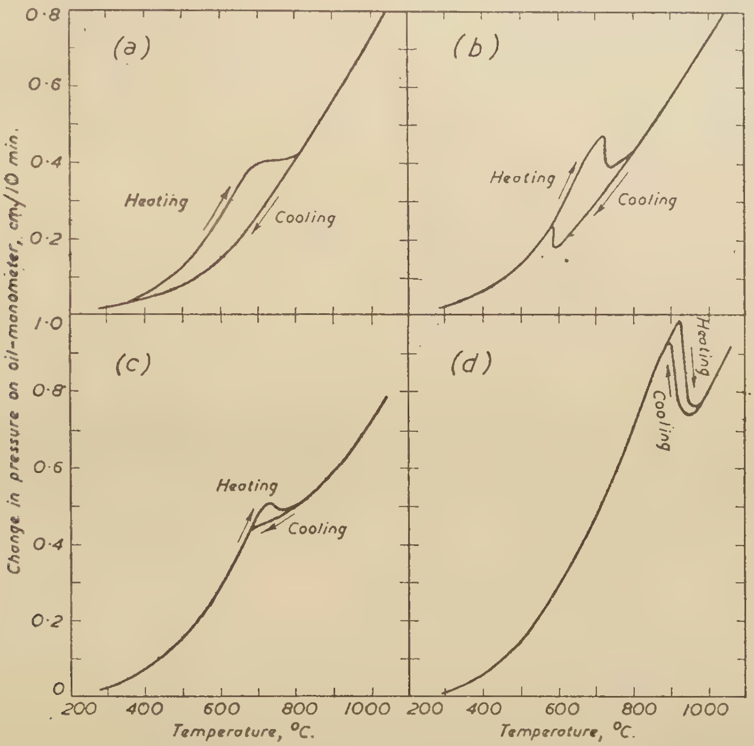


FIG. 37.—Diffusion Curves: (*a*) 4S11, (*b*) *FA*, (*c*) *M*20, (*d*) Ingot Iron.

was maintained at 680° C. for 24 hr. After this period the oil manometer showed no change in pressure when the system was isolated, and it could therefore be assumed that all the hydrogen had been removed from the specimen. With the specimen still at 680° C., the nitrogen was replaced by hydrogen and the oil manometer closely observed. Within half a minute of the turning on of the hydrogen, the oil manometer registered a change in pressure, and this increased progressively with time until, after 10 min., the rate of change of pressure was about half that corresponding to the normal diffusion rate at this temperature.

A similar experiment was carried out at 900° C. Again, diffusion of hydrogen was detected within half a minute, but the later increase was much more rapid than at the lower temperature, and in 2 min. it had reached half the value obtained in the diffusion experiment at 900° C. The results of the diffusion experiments illustrated in Fig. 37 confirm those obtained by other workers, using iron specimens, to the effect that the rate of diffusion of hydrogen is higher in the α state than at the same temperature in the γ state; furthermore, the conclusion may now be drawn that, within the normal range of composition of low-alloy steels, the effect of alloying elements upon the rate of diffusion of hydrogen is negligible.

Evolution of Hydrogen During Heating and Cooling.

After the diffusion experiment on steel 4*S*11 had been completed, the specimen was cooled in nitrogen from 1050° C. and the course of the evolution of hydrogen from the specimen was followed on the oil manometer. When the specimen had cooled to 200° C., the gas which had collected in the inner tube was pumped out, and the specimen was then reheated. The curves obtained on cooling and heating are reproduced in Fig. 38, and probably the most interesting feature is the absorption which occurred as soon as the $\alpha \longrightarrow \gamma$ change had begun; this in spite of the fact that the hydrogen pressure in contact with the steel was only 2 or 3 mm. of mercury. This observation shows clearly that when the γ and α states coexist the hydrogen will tend to concentrate in the austenite.

Since the apparatus was primarily designed for the diffusion experiments, which would entail maintaining a hydrogen atmosphere for several weeks, it was not possible to use a thermocouple in direct contact with the specimen. With the relatively rapid temperature changes occurring in the evolution experiments now being described, it is probable that the thermocouple readings were as much as 100° C. too low on cooling, and correspondingly too high on heating. The temperature scale given in Fig. 38 and for other similar experiments should therefore be regarded as qualitative only.

A somewhat similar experiment was carried out on the ingot-iron specimen. After the

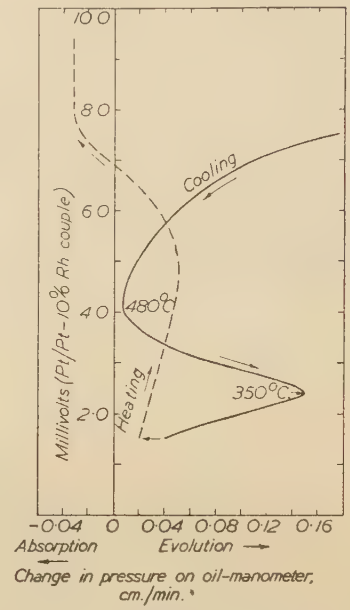


Fig. 38.—Evolution of Hydrogen from 4*S*11 on Cooling and Reheating.

diffusion experiment had been completed, the specimen was reheated in hydrogen and, when the internal hydrogen pressure had reached approximately half an atmosphere, the specimen was allowed to cool in nitrogen from 1050° C., the

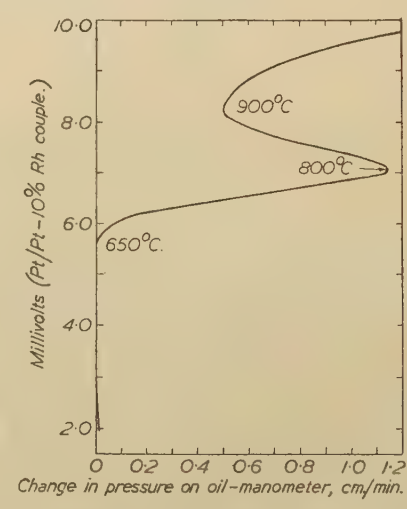


Fig. 39.—Evolution of Hydrogen from Ingot Iron on Cooling.

change in pressure on the oil manometer being taken at 10° C. intervals. The rate of evolution of hydrogen is plotted on an ordinary temperature scale in Fig. 39; it will be seen that from 900° C. downwards the rate of evolution increased and

reached a peak at 800° C. At 650° C., the evolution virtually ceased, which may be taken as an indication that the ingot-iron specimen had lost practically all its hydrogen before reaching that temperature, even with the relatively rapid rate of cooling (about 10° C./min.) employed in this experiment.

These results may be compared with those obtained for steel 4*S*11 (Fig. 38). In this case there is a minimum in the rate of evolution at about 480° C.; below this temperature the rate of evolution increases, rising to a maximum at about 350° C.

A similar experimental arrangement has been used to follow the evolution of hydrogen from large specimens on air-cooling. The soaking furnace described in a previous paper[1] was used, with the following modifications: an axial hole, ¼ in. in dia. and 1 in. deep, was drilled at one end

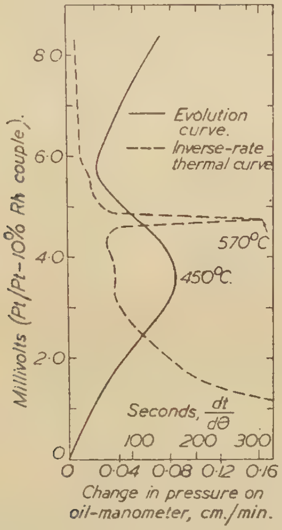


Fig. 40.—Evolution of Hydrogen from *N*22 on Cooling.

of the 4½-in. dia. specimen, to take a ¼-in. dia. small-bore steel tube which was welded to the specimen to make a vacuum-tight joint. This steel tube passed through the base of the furnace in the position previously occupied by the thermocouple and was connected to a vacuum system incorporating pumps and a sensitive oil-manometer. Another small hole was drilled in the top of the specimen to take the thermocouple which was inserted when the furnace had been lifted. The steels examined with this arrangement were the 3¼% nickel steel, *N*22, and a 1½% manganese steel containing 0·35% of carbon, and the soaking periods were 10 hr. at 1100° C. and 10 days at 1000° C., respectively. At the end of the soaking period, the furnace and refractory tube were lifted together, the thermocouple was inserted, and the system connected to the specimen through the small steel tube was evacuated and isolated. Evolution of hydrogen as measured on the oil manometer was recorded simultaneously with the inverse-rate cooling curve. The experimental results for the two steels are given in Figs. 40 and 41 respectively. For the nickel steel, *N*22, and for temperatures above the change point, the evolution of gas was small and decreased as the temperature was lowered. The bulk of the gas was evolved in a peak, with a maximum rate of evolution at 450° C., although the very much sharper peak on the inverse-rate curve occurred at 570° C. A sample of the gas collected throughout this experiment was analysed and found to contain 89% of hydrogen. With the manganese steel, no evolution was detected above 700° C., but as the temperature was lowered further the evolution rapidly increased to a maximum at 560° C., and there was evidence of a subsidiary peak at 420° C. Thermal transformation of this steel was completed within a relatively narrow range, 635–560° C., and the peak on the evolution curve corresponded

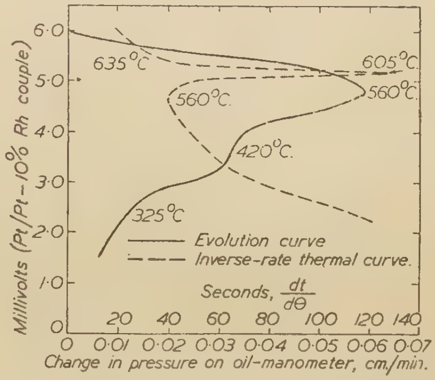


Fig. 41.—Evolution of Hydrogen from *FY* on Cooling.

exactly with the completion of the thermal change. In this experiment, cooling from 1000° to 250° C. took about 3 hr.

These experiments on relatively small specimens of 4*S*11 and of ingot iron, and on larger specimens of *N*22 and the 1·5% manganese steel, lead to the following conclusions:

(i) Evolution of hydrogen diminishes rapidly as the temperature is lowered in the austenite range.

(ii) The main evolution occurs at a temperature which coincides with the completion of thermal transformation.

(iii) In the case of the large specimens, the peak on the evolution curve extends over a much wider range of temperature than does the peak on the inverse-rate curve.

Removal of Hydrogen During Cooling and Reheating.

In a report circulated to the Hair-Line Crack Sub-Committee, Mr. W. J. Dawson gave details

of experiments in which he had been successful in preventing hair-line cracks in small billets of certain steels by reheating them to 650° C. within the incubation period. Some of these billets were forged to 2-in. dia. bar and kindly placed at our disposal for laboratory work. One billet of the manganese–molybdenum steel, *DA*, and three each of the chromium–molybdenum steel, *DB*, and the nickel–chromium steel, *DC*, were available and the following experiments were carried out. Specimens from each billet were soaked in pairs in hydrogen at 1100° C. for 24 hr., after which one was water-quenched and the other cooled in still air. Hydrogen determinations were carried out in the normal manner and the specimens were sectioned and examined for cracks. The results are given in Table XIX.

The most obvious feature of the results is that it is possible for the nickel–chromium steel, *DC*, to retain a greater quantity of hydrogen without the formation of cracks on air-cooling than either the manganese–molybdenum or the chromium–molybdenum steel examined. During the evolution of hydrogen at room temperature under paraffin, the quenched specimens of *DC*1 and *DC*2 showed pronounced incubation periods of 4 and 6 days respectively. With the other steels no sudden evolution of hydrogen was observed.

In another series of experiments specimens of the same steels were soaked in hydrogen, water-quenched, and then reheated to 650° C. Different rates of reheating were employed, the times taken to reach 650° C. being 45 and 15 min. respectively. In all cases the total time of heat-treatment was 2 hr., after which the specimens were quenched in brine, sectioned, and etched to reveal cracks. The results are summarized in Table XX.

From these results it would appear that crack formation in water-quenched standard specimens of the manganese–molybdenum and chromium–molybdenum steels cannot be prevented by reheating. In the case of the nickel–chromium steel, *DC*, however, quick reheating was successful in preventing the formation of internal cracks, although slow reheating failed to do so. It is significant that in the nickel–chromium steel the incubation was marked and a relatively high hydrogen content could be retained in air-cooled specimens without crack formation.

Similar experiments were carried out on a variety of steels, and the hydrogen contents of the water-quenched and of the water-quenched and reheated specimens were determined. The results are given in Table XXI.

It will be seen that the treatment was successful

Table XIX.—*Effect of Water-Quenching and Air-Cooling on 2-in. dia. Billets.*

Steel.	Water-Quenched.		Air-Cooled.	
	H_2 Content, c.c./100 g.	Description of Cracks.	H_2 Content, c.c./100 g.	Description of Cracks.
DA	6·35	Many fine, medium-length radial.	3·38	A single deep-seated crack about 7 mm. long.
*DB*1	6·48	Numerous, medium radial; some short circumferential about 1 mm. below surface; 2 long radial quenching cracks.	3·30	8 typical hair-line cracks, deep-seated and random.
*DB*2	5·80	Numerous rather fine radial cracks.	1·46	6 internal cracks.
*DB*3	7·93	Very numerous; mixture of fine and medium, radial.	2·36	Single internal crack about 6 mm. long.
*DC*1	6·69	Mixture of short, medium and long radial cracks.	4·45	No cracks.
*DC*2	5·66	,, ,, ,, ,, ,,	3·60	,,
*DC*3	5·88	About 50 medium to long, rather wide cracks.	3·63	,,

Table XX.—*Effect of Different Rates of Reheating on 2-in. dia. Billets.*

Steel.	Slow Reheating.	Quick Reheating.
DA	Several short radial cracks.	One or two very fine cracks.
*DB*1	Many fine radial cracks.	Many extremely short radial cracks.
*DB*2	Very numerous short fine radial cracks.	Very numerous short radial cracks.
*DB*3	Several extremely fine radial cracks with 3 severe quenching cracks.	Many short to medium radial cracks.
*DC*1	Many short radial cracks.	No cracks.
*DC*2	Very many short radial cracks.	3 severe quenching cracks extending to surface; no internal cracks.
*DC*3	Quenching cracks extending to surface and a few short radial cracks.	2 quenching cracks extending to surface; no internal cracks.

TABLE XXI.—*Effect of Reheating on Hydrogen Content and Crack Formation.*

Steel.	Water-Quenched and Aged R.T.*		Water-Quenched and Reheated to 650° C.	
	H_2 Content, c.c./100 g.	Description of Cracks.	H_2 Content, c.c./100 g.	Description of Cracks.
*C*11	R.T. 1·68 Heating 4·39 Total 6·07	Many long and extremely straight cracks.	R.T. 0·0 Heating 0·86 Total 0·86	None.
*S*65	R.T. 2·43 Heating 3·70 Total 6·13	Numerous, fine and rather short.	R.T. 0·0 Heating 0·37 Total 0·37	About 10 or 12 short cracks.
FA †	R.T. 3·38 Heating 3·07 Total 6·45	Relatively few, but long.	R.T. 0·06 Heating 0·22 Total 0·28	2 short cracks.
4*S*11	R.T. 2·92 Heating 3·61 Total 6·53	Numerous, fine short and long cracks mixed.	R.T. 0·06 Heating 0·37 Total 0·43	Many short radial cracks.
*C*10	R.T. 1·55 Heating 5·02 Total 6·57	Many medium-length straight cracks.	R.T. 0·0 Heating 0·57 Total 0·57	1 short crack.
FY † 1·5% Mn, 0·35% C.	R.T. 2·81 Heating 3·97 Total 6·78	6 long and coarse with some very fine and short.	R.T. 0·05 Heating 2·08 Total 2·13	2 long with many short, fine radial cracks.
*A*114	R.T. 2·70 Heating 4·81 Total 7·51	3 very long and many medium-length fine cracks.	R.T. 0·02 Heating 0·86 Total 0·88	4 medium cracks.
MC	R.T. 3·10 Heating 4·66 Total 7·76	Medium cracks, not radial, at centre of specimen.	R.T. 0·05 Heating 0·82 Total 0·87	None.
ATW (American) 1·5% Mn, 0·3% Mo.	R.T. 3·79 Heating 4·38 Total 8·17	Medium-length zigzag cracks.	R.T. 0·03 Heating 0·49 Total 0·52	None.
CM	R.T. 5·23 Heating 4·35 Total 9·58	Several very long cracks with many short and fine ones.	R.T. 0·05 Heating 0·70 Total 0·75	None.

* R.T. = Room temperature.
† *FA*, and the 1½% manganese steel, *FY*, were reheated to 650° C. in 45 min., as compared with 15 min. for all other specimens.

for steels *CM*, *ATW*, *MC*, and *C*11, and clearly unsuccessful for steels 4*S*11, *FY*, *S*65, and *A*114, while *FA* and *C*10 were borderline cases in that only one or two short cracks were observed in the cross-section. The initial hydrogen content by itself does not decide whether or not reheating is successful, as may be seen from the fact that successful results were obtained with *CM*, containing 9·58 c.c./100 g., whereas none of the steels for which treatment was unsuccessful contained more than 7·0 c.c./100 g. before reheating.

In another series of experiments standard specimens of the manganese–molybdenum steel *N*17 were soaked in hydrogen at 1100° C. and water-quenched, then rapidly reheated by being plunged into the lead or salt bath controlled at the required temperature. One specimen was removed from the bath after 10 min., and the other after 2 hr., and both were water-quenched. Hydrogen determinations and examination for cracks were carried out in all cases and the results are given in Table XXII.

A period of 7 days elapsed between the reheating treatment and heating for hydrogen determination, so that it may be concluded that, with this steel and this size of specimen, it is possible to avoid cracks if reheating is sufficiently rapid and if the temperature is sufficiently high. Reheating by plunging into the salt or lead bath is extremely rapid, and this causes the hydrogen contents of the specimens treated for 10 min. at 500° and 650° C., respectively, to be appreciably lower than those for the specimens treated similarly at 200° and 350° C.

In a previous paper [1] it was shown that with the *D* series of nickel–chromium–molybdenum steels

the effect upon crack formation of reheating to 650° C. was progressively more marked as the carbon content was increased, and it was possible to link this up with the temperature at which the lowest peak occurred on the evolution curve of the corresponding steel. In discussing these results it was stated that ". . . in the extreme case it may even be possible, with a specimen containing a stable hydrogen-rich constituent to reheat in such a manner as to prevent hair-line cracks. Thus it is conceivable that by sufficiently rapid heating breakdown of the constituent might be postponed to a temperature range in which the rate of diffusion is so high that the hydrogen released by breakdown of the hydrogen-rich constituent can readily leave the metal, and no void would be able to retain hydrogen under pressures sufficient to disrupt the steel."

Table XXII.—*Effect of Reheating upon Hydrogen-Soaked, Water-Quenched Specimens of Mn–Mo Steel,* N17.

Treatment.	H_2 Content, c.c./100 g.	Description of Cracks.
10 min. at 200° C.	5·25	Very numerous, fine and radial.
2 hr. at 200° C.	3·28	Few, short, fine and radial.
10 min. at 350° C.	5·16	Medium, radial.
2 hr. at 350° C.	2·90	Very short, radial—almost dots.
10 min. at 500° C.	4·71	Medium cracks, some radial, some deep-seated and random.
2 hr. at 500° C.	1·27	No cracks.
10 min. at 650° C.	3·66	"
2 hr. at 650° C.	0·85	"

Effect of Hydrogen upon Transformation.

If the theory of crack formation put forward in an earlier paper [1] is sound, it would follow that hydrogen must exert an influence upon the $\gamma \longrightarrow \alpha$ transformation; various experiments were therefore carried out with the object of detecting any such effect. Thus inverse-rate heating and cooling curves were taken in hydrogen, and the results compared with those for control specimens heated in vacuum or in nitrogen. No significant difference was observed when the nickel–chromium–molybdenum steels, 4*S*11 and *F*1, and the 3% nickel steel, *F*5, were used. It was thought that the method was probably too insensitive and that more satisfactory results might be obtained if the effect of hydrogen upon the transformation was investigated over a range of temperatures. Accordingly the isothermal transformation characteristics of the steel 4*S*11 have been examined in some detail.

In normal work on isothermal transformation the specimens are made as small as practicable, in order to ensure rapid and uniform cooling, but since in the present case it was desired to retain as much hydrogen as possible, it was decided to use specimens of 1-in. dia., as it was known that hair-line cracks could be produced in such specimens. To eliminate effects which might be due to the large specimen size, direct comparison was made in all cases between specimens which had been soaked in hydrogen and those which had been given identical treatment in nitrogen.

All the specimens were soaked in nitrogen or hydrogen at 1150° C. for 4 days, before transference to a bath of molten alloy controlled at the required temperature. Preliminary experiments showed that the grain-size was the same in nitrogen- and hydrogen-treated specimens. The general transformation characteristics were first explored by means of a suitable dilatometer, using specimens 2 in. long by 1 in. dia. A hydrogen- or nitrogen-soaked specimen was rapidly transferred to the preheated dilatometer, which was then lowered into the isothermal bath. No appreciable difference was observed in the induction period for nitrogen- and hydrogen-treated specimens except at 550° C., when it was found that transformation of the nitrogen-soaked specimen commenced after approximately 1 day, whereas the hydrogen-treated specimen showed no transformation until the end of 2 weeks. Whether the transformation was apparently completed or not at a given temperature, the expansion observed for the nitrogen-treated specimen was always greater than for the hydrogen-treated specimen, within the range 330–600° C. The dilatation curves obtained at 330°, 400°, and 450° C. indicated that a steady state had been reached, but changes in length were still slowly occurring after 19 days at 550° C. or 2 days at 600° C. In order to compare the relative amounts of untransformed austenite in the nitrogen-soaked and in the hydrogen-soaked specimens after the same isothermal treatment, further dilatation specimens were held at 500°, 550°, and 600° C., respectively, for 24 hr., and the dilatometer was then removed from the lead bath and used to measure the changes in length accompanying the transformation of the austenite on cooling. The dilatation curves obtained in this manner are reproduced in Fig. 42. The results show that 24 hr. at 500° C. is sufficient to ensure the complete transformation of the nitrogen-treated specimen, whereas the dilatation curve for the corresponding hydrogen-soaked specimen reveals the presence of a small quantity of austenite. At 550° C. the difference between the nitrogen- and hydrogen-treated specimens is very marked, the hydrogen-treated specimen showing an expansion of 57×10^{-4} in., whereas the control specimen expanded only

22×10^{-4} in. This is in agreement with the dilatation curves taken at 550° C., which showed that only the nitrogen-treated specimen commenced to transform in the first 24 hr. Both specimens isothermally treated at 660° C. had partially transformed within the first 24 hr., but

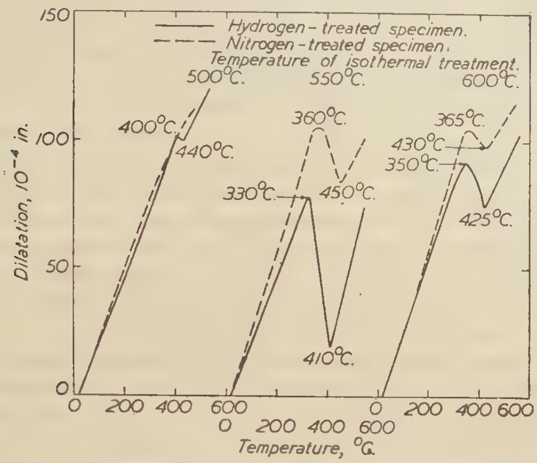


FIG. 42.—Dilatation of Steel 4S11 on Cooling from Isothermal Bath.

in this case also there was more untransformed austenite in the hydrogen-treated than in the nitrogen-treated specimen.

After this preliminary exploration with a dilatometer, the field was explored in greater detail metallographically. Six specimens of 1 in. dia. and 1 in. in length were treated and quenched together in the lead bath; after periods based on the dilatometric curve already obtained for the particular temperature, they were in turn removed and quenched in brine. Each specimen was then sectioned, and one half was polished for micro-examination and the other for hardness measurements. Both nitrogen- and hydrogen-treated specimens showed signs of decarburization in an outer ring about $\frac{1}{8}$ in. in thickness, and therefore all observations were confined to a central area of $\frac{1}{2}$-in. dia., which was unaffected. Specimens were etched, to show the transformation products clearly against a background of lightly etched martensite, and were then explored thoroughly; a typical area was selected and photographed at a magnification of 100 diameters. A tracing of the negative was taken on squared paper and the area occupied by the transformation products was measured independently by two workers. To express the results numerically, the area occupied by the transformation products was expressed as a percentage of the total area of the field and taken as the percentage of transformation. To express the results in graphical form, the method described by Austin and Rickett [3] was adopted. These workers found that the transformation of austenite at constant temperature could be represented by an empirical equation of the type:

$$\mathrm{Log}\frac{P}{100 - P} = k \log t + C,$$

where P is the percentage transformed at time t. They also showed that, if the percentage transformed is plotted on an autocatalytic scale against log t, a straight-line relationship is obtained which facilitates extrapolation to the beginning and end of transformation. The results plotted in this manner are given in Fig. 43.

It will be seen that the experimental points lie reasonably well on straight lines, as stated by Austin and Rickett, and the results justify the conclusion that, as far as the nickel–chromium–molybdenum steel, 4S11, is concerned, and within the range examined, the effect of hydrogen treatment is to retard the transformation at temperatures above 450° C. Below this temperature the effect of hydrogen is small, but, if anything, it tends to accelerate the transformation. This effect at the lower temperature was shown clearly by the hardness determinations. Thus, for the hydrogen-treated specimens, the hardness reached

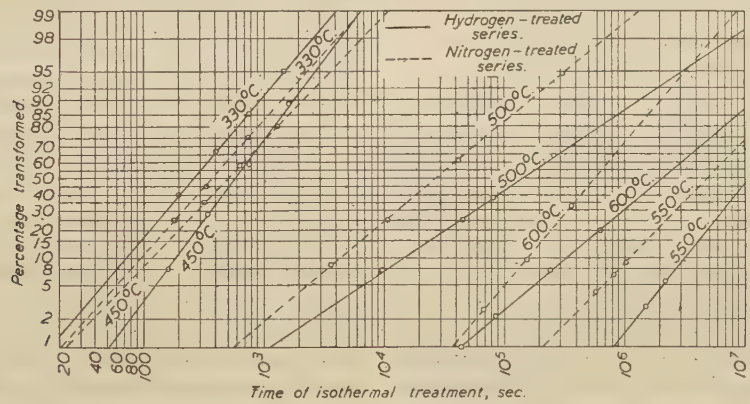


FIG. 43.—Isothermal-Transformation Data, Hydrogen- and Nitrogen-Treated 4S11, plotted on autocatalytic scale.

a constant value after 5 min. at 400° C., or 20 min. at 350° C., whereas the hardness value of the corresponding nitrogen-treated specimens was greater and was still falling after longer periods. In general, the hardness determinations gave confirmation of the results of dilatometric and micro-examination. At temperatures other than 550° C., hydrogen appeared to have little effect upon the period of induction.

The hardness specimens were etched to reveal hair-line cracks, and the results obtained are summarized in Fig. 44. No internal cracks were observed in any of the specimens which had been treated in nitrogen, but all of the hydrogen-soaked specimens which were quenched from the shaded area of Fig. 44 contained hair-line cracks. Specimens quenched from points outside this area showed no internal cracks. For convenience, the curves indicating the beginning and ending of transformation are also drawn in Fig. 44, and it

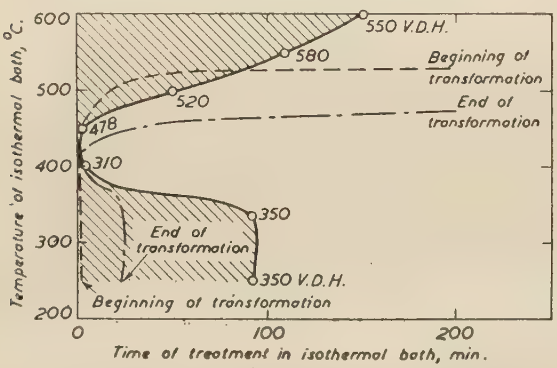


FIG. 44.—Relation between Crack Formation and Transformation Characteristics of 4S11.

will be seen that, by giving a suitable isothermal treatment at 550° or 600° C., it was possible to avoid hair-line cracks, although transformation had not even commenced when the specimen was quenched in brine. On the other hand, it was possible to obtain cracks in specimens quenched from temperatures of 250–375° C., although transformation of the steel was complete before quenching. Since it was found that sufficiently long soaking at these temperatures would eliminate cracks, it followed that the cracks could not have been formed during the process of transformation, and therefore that transformation stresses could not have been the cause of the cracks observed. It is interesting to note that after $3\frac{1}{2}$ min. at 330° C., the steel was about 40% transformed and there were many radial cracks, whereas after $6\frac{1}{2}$ min. the steel was about 65% transformed and the cracks were deep-seated and random.

In another series of experiments, standard Jominy test-pieces were soaked in hydrogen or nitrogen at 1050° C. for various lengths of time up to 70 hr. After end-quenching, the specimens were prepared by wet-grinding a flat to a depth of 0·25 in., the last 0·015 in. being removed 0·001 in. at a time. After final hand-finishing on emery paper, diamond pyramid hardness measurements were taken at $\frac{1}{20}$-in. intervals along the midline of the flat, using a 30-kg. load. Most work was carried out on the 3% nickel steel, N22, and comparison of the results obtained for hydrogen- and nitrogen-treated specimens showed no difference at the hardened end, but possibly 10 or 20 points difference in the slowly cooled parts, where the hydrogen-treated specimens tended to be harder. With the nickel–chromium–molybdenum steels, 4S11 and S65, and the manganese–molybdenum steel, FA, no difference was found between the behaviour of the hydrogen- and nitrogen-treated specimens. With a view to accentuating any effect which hydrogen might have, specimens 2 in. long by $1\frac{3}{4}$ in. dia. of steels 4S11, S65, and FA were soaked in hydrogen or nitrogen, and oil-quenched or air-cooled. Hardness determinations were carried out on a suitably prepared mid-transverse section, but no significant difference in hardenability was detected between hydrogen- and nitrogen-soaked specimens.

Bearing in mind the work* on the isothermal transformation of steel 4S11, these results are quite understandable. In 4S11, at least, the effect of hydrogen is to retard the transformation at temperatures above 450–500° C., yet with the steels employed, except N22, the transformation on cooling occurs below 500° C. Assuming that the effect of hydrogen upon these steels is similar, it is clear that no change in hardenability can be expected when 4S11, S65, or FA is used. With steel N22, the change-point on cooling occurs at about 570° C., and any retarding effect of hydrogen upon the transformation would be expected to make the steel harder in those parts of the Jominy test-piece which are cooled slowly.

With a view to obtaining more information about the effect of hydrogen upon transformation during cooling, a dilatometer was constructed to take specimens of 1 in. dia. and 4 in. in length. This consisted essentially of a long fused-silica tube and two solid-silica rods, one of which transmitted changes of length of the specimen to the sensitive dial-gauge which was attached to one end of the silica tube. The other silica rod pushed against an end plate, which was fitted with a screw adjustment and openings for the admission of a thermocouple. In order to ensure a uniform temperature throughout the specimen during cooling, the middle part of the silica tube, where the specimen was situated, was placed in a furnace maintained at a suitable temperature. As soon as the hydrogen- or nitrogen-soaked hot specimen had been quickly transferred to the dilatometer, the furnace was switched off and the specimen allowed to cool with the furnace. By adjusting

the furnace temperature it was possible to obtain various rates of cooling, particularly in the higher temperature ranges.

Dilatation curves were obtained on steels *FY*, 4*S*11, *FA*, *CM*, and a case-hardening 3% nickel steel, *CH*, after soaking in hydrogen or nitrogen at 1100° C. for 24 hr., and the results are given in Figs. 45 and 46. Probably the most interesting feature is that the hydrogen-soaked specimens in each case showed some 20–30% less expansion at the $\gamma \longrightarrow \alpha$ transformation than

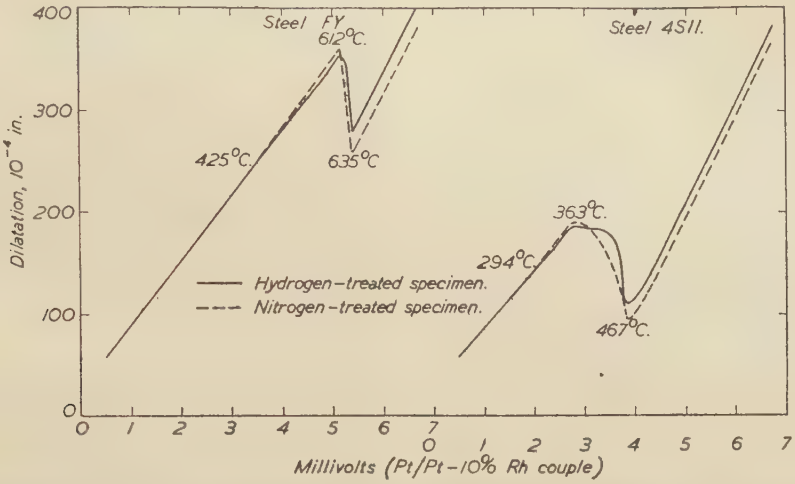


FIG. 45.—Dilatation Curves of Hydrogen- and Nitrogen-Treated Specimens on Cooling from 1100° C.

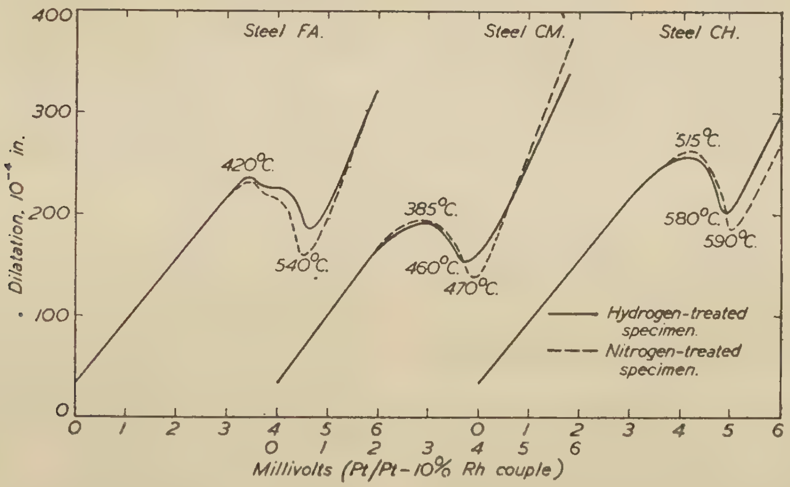


FIG. 46.—Dilatation Curves of Hydrogen- and Nitrogen-Treated Specimens on Cooling from 1100° C.

the corresponding nitrogen-soaked specimen. The slope of the curve obtained for the hydrogen-treated specimen of the 3% chromium–molybdenum steel, *CM*, in the austenitic region is abnormal, but it is not clear whether this should be attributed to the effect of hydrogen or not. The difference in expansion occurring at the transformation could be explained in terms of the retention of austenite by hydrogen, but another possibility is that the austenite lattice is expanded by the hydrogen in solution to a greater extent than the α lattice which is formed from it, and which contains considerably less hydrogen, so that the apparent expansion on transformation is less.

Formation of Hair-Line Cracks under Various Conditions.

A specimen of 4*S*11 steel, 3 in. long by $1\frac{3}{4}$-in. dia., was soaked in hydrogen at 1100° C. for 48 hr., after which it was cooled in air. When a sensitive dial-gauge indicated that the expansion at the transformation was completed, the specimen was quenched in water and was immediately cut half-way through at the mid-transverse section and then half-way longitudinally, so that a quarter of the specimen was removed. The remainder of the specimen was allowed to age at room temperature for 2 days, after which the longi-

tudinal cut was completed, and the whole longitudinal section was etched to reveal cracks (*see* Fig. 13). The black line in Fig. 13 corresponds to the first transverse saw-cut. It is clear from the photograph that the first longitudinal saw-cut was commenced before the incubation period was over, but that the last $\frac{1}{2}$ in. or so coincided with the first stages of crack formation. The 2 days' ageing at room temperature were sufficient to enable numerous cracks to be formed in the lower half of the specimen. Micro-examination of the specimen revealed the presence of appreciable areas of martensite, particularly near the centre of the specimen, and it was found that the cracks were, for the most part, intercrystalline and showed no preference for hard or soft areas.

Standard specimens of the ball-bearing steel, *N*31, were soaked in hydrogen and then water-quenched or cooled in air. After ageing for 1 week at room temperature under paraffin, the specimens were heated for hydrogen determinations and were then sectioned and examined for cracks. The quenched specimens showed quenching cracks but no internal cracks, whereas hair-line cracks were always obtained in the air-cooled specimens. The hydrogen contents determined in the normal manner were 7·43 and 4·64 c.c./100 g. for the water-quenched and air-cooled specimens respectively. Similarly, with this steel, cracks were not observed in a hydrogen-soaked specimen which was quenched from immediately above the Ar_1 change-point, but were numerous in another specimen which was quenched as soon as the expansion at the transformation was apparently complete. This behaviour of *N*31 is quite different from that of other steels. Thus, water-quenched specimens of steels *C*10, *CM*, and *N*17, with hydrogen contents of 6·57, 9·58, and 7·13 c.c./100 g. respectively, showed many radial cracks, while the air-cooled specimens of *C*10 and *N*17, with hydrogen contents of 3·39 and 2·10 c.c./100 g. respectively, showed one or two cracks; the corresponding *CM* specimen, which contained 3·75 c.c./100 g., was completely free from cracks.

As might be expected, the composition of the steel plays an important part in determining the amount of hydrogen lost during the transformation, but a steel which loses more hydrogen at the transformation is not necessarily less susceptible to crack formation. This is illustrated by the results obtained for the nickel–chromium–molybdenum steel, *V*30, and the manganese–molybdenum steel, *DA*. The hydrogen content of these two steels, after quenching from just above the change-point, were 5·96 and 5·65 c.c./100 g., respectively, and both contained numerous radial cracks. The nickel-chromium-molybdenum specimen, quenched immediately below the Ar_1 change-point, contained 2·50 c.c./100 g. and showed one internal crack in the section examined, whereas the corresponding manganese–molybdenum specimen retained 4·60 c.c./100 g., but was free from cracks.

The anomalous behaviour of the ball-bearing steel *N*31 was further investigated by giving a hydrogen treatment to specimens 4 in. long by $1\frac{3}{4}$-in. dia. and then carrying out a Jominy end-quench. A longitudinal flat was ground sufficiently deep to remove the decarburized layer, and diamond pyramid hardness measurements were taken along the length of the specimen; the results are given in Fig. 50. After ageing for a week at room temperature, the specimen was softened and sectioned longitudinally before etching, to reveal the internal cracks, which are also illustrated in Fig. 50. The most interesting feature is the complete absence of cracks in the quenched end, while the upper zone, which cooled more slowly, contained many cracks. Fig. 50 shows that the hardness in the crack-free zone varies from 600 to 720, whereas the hardness where the cracks appear is generally about 500.

Similar experiments were carried out on a variety of steels, and the results are given in Table XXIII. and illustrated in Figs. 51 to 57. In contrast with the steel *N*31, the tyre steel, *K*6, contained cracks only near the quenched end, the softer regions being completely free from cracks. There appears to be no direct connection between hardness and crack formation, however, for in the one steel it is possible for cracks to appear in the hard zone and not in the soft (*e.g.*, *K*6) or *vice versa* (*e.g.*, *N*31), or even for cracks to occur in both hard and soft zones while at the same time an intermediate region is completely free (*e.g.*, *S*69).

The general appearance and distribution of the cracks in the $3\frac{1}{2}\%$ nickel steel, *S*69, the nickel–chromium–molybdenum steel, *V*30, and the manganese–molybdenum steel, *N*17, are similar, although these steels differ widely in composition. On the other hand, though both *N*17 and *MM* are nominally $1\frac{1}{2}\%$ manganese–molybdenum steels, the appearance of the cracks in the two specimens differs very considerably, particularly near the quenched end. Compared with the other alloy steels examined in this way, the nickel–vanadium steel, *NV*, and the chromium–molybdenum steel, *DB*, show very few cracks, and the distribution is somewhat similar in the two cases.

To assist in assessing these results, the temperatures at different positions in the specimen were measured during quenching. The specimen used for this purpose was the nickel–chromium steel, *DC*, and longitudinal holes of $\frac{3}{16}$ in. dia. were drilled to depths of $\frac{1}{2}$, $1\frac{1}{2}$, $2\frac{1}{2}$, and $3\frac{1}{2}$ in., respectively, from the top and at equal distance from the axis.

Simultaneous temperature readings were taken at intervals of 30 sec. and the results are plotted in the form of cooling-rate curves in Fig. 47. The direct cooling curves obtained showed reduced cooling rates in certain temperature ranges due to the transformation. In the hot end of the specimen the temperature range was approximately from 525° to 325° C., and as this range would include the transformation on cooling of most of the steels examined, the curves shown in Fig. 47 may be regarded as representative. The cooling curve for the position $\frac{1}{2}$ in. from the quenched end showed reduced cooling rates due to transformation in the neighbourhood of 200° C. The reduced cooling rates due to transformation at different temperatures are the cause of the overlapping of the curves of Fig. 47, in which rate of cooling is plotted against position in the specimen.

Effect of Hydrogen upon Mechanical Properties.

It has been known for some time that hydrogen causes embrittlement of steel, and once it is accepted that hair-line cracks occur only when the steel contains sufficient hydrogen, a detailed knowledge of the effect of this element upon the mechanical properties becomes highly desirable. Zapffe and Sims [4] have carried out much work on the effect of hydrogen upon the mechanical properties of iron and carbon steels, but relatively little upon low-alloy structural steels. In the present work tensile tests were used, because preliminary experiments showed that the Izod impact test was relatively less sensitive to the presence of hydrogen. This is illustrated by the results obtained for the 3% chromium–molybdenum steel, *CM* (reported in Table XXIV.),

TABLE XXIII.—*Appearance of Cracks in End-Quenched, Hydrogen-Soaked Specimens.*

Steel.	Fig. No.	Distance of Cracks from Quenched End, in.	Hardness Range.	Description of Cracks.
*N*31	50	0·0–$2\frac{1}{8}$	720–600	No cracks.
		$2\frac{1}{8}$–4	600–490	Many medium, zigzag cracks with a tendency to be transverse.
*K*6	51	0–$\frac{1}{4}$	675–530	Mixture of very long transverse cracks, with dots near quenched end.
		$\frac{1}{4}$–$\frac{5}{8}$	530–335	Single longitudiual crack on axis.
		$\frac{5}{8}$–4	335–245	No cracks.
NV	52	0–$\frac{1}{8}$	655–630	Numerous dots, and very short cracks.
		$\frac{1}{8}$–$\frac{3}{8}$	665–640	A few medium-length cracks.
		$\frac{3}{8}$–$1\frac{5}{8}$	640–325	No cracks except a very severe quenching crack.
		$1\frac{5}{8}$–$3\frac{1}{8}$	325–260	14 zigzag medium cracks in random distribution.
		$3\frac{1}{8}$–4	Below 260	A single short longitudinal crack.
*S*69	53	0–$\frac{1}{2}$	670–690	Very numerous medium cracks, with some dots very near quenched end.
		$\frac{1}{2}$–$1\frac{1}{2}$	670–640	Mixture of medium to long transverse and longitudinal cracks.
		$1\frac{1}{2}$–$2\frac{1}{4}$	640–560	No cracks.
		$2\frac{1}{4}$–$3\frac{1}{2}$	560–375	Many medium-length longitudinal with a few short random cracks.
		$3\frac{1}{2}$–4	375–300	A cluster of 10 small to medium transverse cracks.
DB	54	0–$\frac{3}{8}$	385–280	A few short cracks.
		$\frac{3}{8}$–$\frac{3}{4}$	280–240	No cracks.
		$\frac{3}{4}$–4	240–230	A few medium to long zigzag longitudinal cracks.
*N*17	55	0–$1\frac{1}{2}$	565–530	Long and widely spaced cracks, with a tendency to transverse.
		$1\frac{1}{2}$–3	530–400	All cracks longitudinal, shorter and more zigzag.
		3–4	390	Very short cracks in random distribution.
MM	56	0–$\frac{5}{8}$	600–575	1 longitudinal quenching crack.
		$\frac{3}{4}$	565	1 long, broad, transverse crack.
		1	500	1 long, broad, transverse crack.
		1–$2\frac{1}{2}$	500–300	Mixture of short random with medium transverse cracks.
		$2\frac{1}{2}$–4	295	Numerous short longitudinal cracks.
*V*30	57	0–$\frac{1}{4}$	515–495	No cracks.
		$\frac{1}{4}$–$1\frac{1}{4}$	495–475	Mixture of medium, long, and very long cracks distributed at random around an oval zone free from cracks.
		$1\frac{1}{4}$–$1\frac{1}{2}$	475–450	No cracks.
		$1\frac{1}{2}$–3	450–320	Several medium random and many very short and fine longitudinal cracks near the axis.
		3–4	320–300	2 short cracks.

for tensile specimens of 2 in. gauge length and 0·564 in. dia., and for Izod specimens of 1-cm. sq. cross-section.

The tensile test results for a number of steels

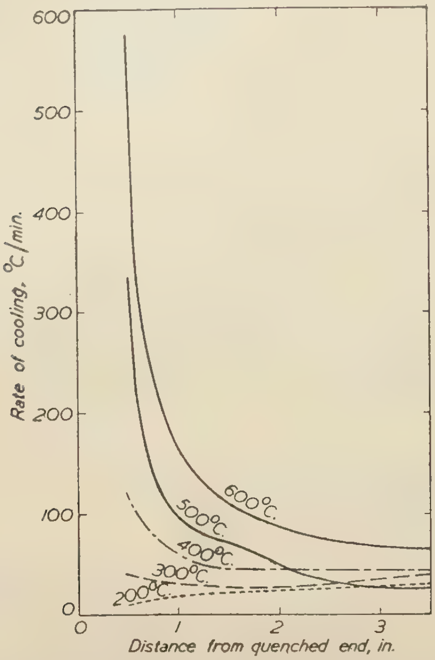


Fig. 47.—Cooling Rates at Various Temperature Levels along a $1\frac{3}{4}$-in. dia. Specimen during Jominy End-Quenching.

after various treatments in hydrogen or nitrogen are given in Table XXV.

It is convenient to consider the effect of hydrogen upon the individual mechanical properties of those steels which have received a standard treatment of 24 hr. at 850° C. in hydrogen or nitrogen, followed by air-cooling.

Table XXIV.—*Effect of Hydrogen upon Mechanical Properties of* 3% *Cr–Mo Steel*, CM.

Heat-Treatment.	Heat-Treatment Atmosphere.	Izod, ft. lb.	Elongation on 2 in., %.	Reduction of Area, %.
A.C. from 850° C.	Hydrogen.	39	4·5	7·0
	Nitrogen.	46	18·0	56·0
O.Q. from 850° C.	Hydrogen.	38	...	...
	Nitrogen.	54	...	...

In order to compare the effects of hydrogen upon different steels, the ratio between the given mechanical property for the hydrogen-treated and nitrogen-treated specimens will be taken.

Limit of Proportionality.

Results are available only for ten steels and the corresponding numerical values of the ratio are given in Table XXVI. Thus, the limit of proportionality was exactly the same for hydrogen- and nitrogen-treated specimens of *N*33 and *N*31, whereas for the other steels examined the limit of proportionality was lower in all cases for the hydrogen-treated specimens. In the worst case, *N*21, the limit of proportionality was reduced from 20·0 to 8·0 tons/sq. in.

Proof Stress.

The 0·1% proof stress was determined for the same steels and the ratio between hydrogen- and nitrogen-treated specimens was calculated. The proof stress appears to be less affected by hydrogen than is the limit of proportionality; the ratios are given in Table XXVI.

Maximum Stress.

Hydrogen treatment appeared to have little effect upon the maximum stress, except for steels *N*23 and *N*23Mo, as is shown in Table XXVI.

Breaking Stress.

The ratio between the breaking stress on the reduced cross-section for the hydrogen-treated specimen and that for the control specimen treated in nitrogen varies considerably, although there appears to be no systematic variation with composition. The values of this ratio are given in Table XXVI. The results for *S*69 appear anomalous, particularly when the figures for elongation and reduction in area are considered, but steel for repeating the experiment was not available.

Reduction in Area.

The results obtained for reduction in area are reclassified in Table XXVI. It will be seen that the reduction of area is most seriously reduced in the case of the nickel–chromium steel, *N*23, the nickel–chromium–molybdenum steel, *V*30, and the two chromium–molybdenum steels, and that the other steels examined fall in another category for which the effect, although still present, is far less marked. *N*23Mo was least affected, and this is difficult to understand, when the behaviour of *N*23 and *V*30 is taken into account. *N*23 and *N*23Mo were treated simultaneously in the same furnace.

Elongation.

The elongation results show the same general tendency as those for reduction in area, as will be seen from Table XXVI.

Of the ten steels for which measurements of limit of proportionality and proof stress are available, it can be said that hydrogen has a pronounced effect upon the limit of proportionality in the case of *N*21, *S*69, and *N*37 and upon the proof stress for *N*21. The maximum stress

TABLE XXV.—*Tensile Test Results for Steels after Various Treatments in Hydrogen or Nitrogen.*

Steel.	Atmosphere.	Treatment.	Limit of Proportionality, tons/sq. in.	Proof Stress, tons/sq. in.	Max. Stress, tons/sq. in.	Breaking Stress on Reduced Area, tons/sq. in.	Reduction of Area, %.	Elongation on 2 in., %.	H_2 Content, c.c./100 g.
*S*69	H_2	24 hr., 850° C., A.C.	10·0	28·0	66·0	69·7	11·0	9·0	1·16
	N_2		17·8	31·0	64·0	64·1	22·0	11·0	...
*S*69	H_2	Heated to 1080° C., F.C. to 380° C., and W.Q.	...	...	56·2	58·2	3·5	1·5	2·13
	N_2		...	...	64·0	73·8	16·0	6·2	...
*S*69	H_2	10 days at 650° C. and W.Q.	12·6	21·2	44·2	70·0	50·0	18·0	1·0
	N_2		14·8	22·6	48·0	76·3	45·0	22·0	...
*S*69	H_2	3 hr., 850° C., A.C.	13·8	30·0	67·6	70·4	6·0	4·5	...
	N_2		18·0	31·0	74·4	75·4	17·5	7·8	...
*N*21	H_2	24 hr., 850° C., A.C.	8·0	21·4	47·6	56·9	22·0	10·0	1·52
	Moist H_2		...	...	45·8	55·9	22·0	8·9	...
	N_2		20·0	28·2	48·0	70·4	39·5	14·0	...
*N*21	H_2	24 hr., 850° C., A.C., reheated 135° C. for 2 hr.	...	...	47·8	66·5	35·0	17·6	...
	H_2	24 hr., 850° C., A.C., reheated 135° C. for 6 hr.	...	...	47·2	84·7	49·5	22·0	...
	H_2	24 hr., 850° C., A.C., reheated 135° C. for 24 hr.	16·6	24·8	47·0	87·4	51·5	22·0	...
	N_2		22·0	29·6	47·2	87·1	52·0	23·0	...
	H_2	24 hr., 850° C., A.C., reheated to 650° C. and W.Q.	...	...	44·4	79·0	58·0	29·0	...
	N_2		...	...	44·4	78·6	58·0	29·6	...
*N*33	H_2	24 hr., 850° C., A.C.	10·0	18·8	37·4	50·1	32·5	24·0	1·16
	Moist H_2		10·0	19·2	37·0	50·4	32·5	23·0	...
	N_2		10·0	19·6	37·2	85·6	61·0	33·6	...
*N*33	H_2	24 hr., 850° C., A.C., reheated to 650° C. and W.Q.	...	...	37·2	76·8	68·5	27·0	...
	N_2		...	...	37·4	78·1	69·0	27·0	...
	H_2	24 hr., 850° C., A.C., reheated 105° C. for ½ hr.	...	...	37·8	56·8	40·0	26·5	...
	H_2	24 hr., 850° C., A.C., reheated 105° C. for 4¾ hr.	...	...	37·8	71·0	59·6	32·0	...
	H_2	24 hr., 850° C., A.C., reheated 105° C. for 24 hr.	11·2	19·0	37·2	70·5	63·5	33·5	...
	H_2	24 hr., 850° C., A.C., reheated 105° C. for 28¾ hr.	...	...	37·4	72·0	64·0	33·5	...
	N_2	24 hr., 850° C., A.C., reheated 105° C. for 24 hr.	12·0	20·8	37·6	70·0	62·5	33·8	...
*N*37	H_2	24 hr., 850° C., A.C.	10·8	20·2	36·2	55·4	44·0	28·0	2·00
	Moist H_2		10·9	21·9	36·0	56·5	46·5	30·0	...
	N_2		16·6	21·8	35·6	60·5	60·0	30·0	...
*N*37	H_2	24 hr., 850° C., A.C., reheated to 650° C. and W.Q.	...	...	35·8	97·4	69·0	37·0	...
	N_2		...	...	36·0	78·1	69·0	37·0	...
NV	H_2	24 hr., 850° C., A.C.	...	...	57·6	67·1	21·0	7·0	1·83
	N_2		...	...	56·0	76·8	37·0	9·0	...
NV	H_2	24 hr., 850° C., A.C., reheated to 650° C. and W.Q.	...	...	59·8	91·4	49·0	9·5	...
	N_2		...	...	60·4	93·3	49·0	9·5	...
NV	H_2	24 hr., 850° C., A.C., aged 45 days at R.T.	23·0	36·0	60·0	73·8	35·0	14·0	...
	N_2		22·0	37·5	57·0	77·3	40·5	17·0	...
*N*19	H_2	24 hr., 850° C., A.C.	22·0	38·0	60·4	62·3	3·0	0·5	1·26
	N_2		25·6	39·0	70·2	88·6	30·0	11·5	...
*N*19	H_2	24 hr., 850° C., A.C., aged 12 days at R.T.	26·0	45·0	68·8	80·3	20·0	6·0	...
	N_2		25·8	38·0	62·4	83·1	35·0	12·5	...

F.C. = Furnace-cooled. R.T. = Room temperature.

TABLE XXV.—*Continued.*

Steel.	Atmosphere.	Treatment.	Limit of Proportionality, tons/sq. in.	Proof Stress, tons/sq. in.	Max. Stress, tons/sq. in.	Breaking Stress on Reduced Area, tons/sq. in.	Reduction of Area, %.	Elongation on 2 in., %.	H_2 Content, c.c./100 g.
*N*19	H_2	24 hr., 850° C., A.C., aged 45 days at R.T.	21·5	36·0	67·8	88·4	34·2	13·5	...
	N_2		23·0	37·2	63·6	77·0	37·7	15·0	...
*N*19	H_2	24 hr., 850° C., A.C. and reheated 80° C. for 2½ hr.	22·0	41·5	69·0	77·5	13·5	4·0	...
	N_2		25·0	37·5	62·6	81·2	33·0	12·1	...
*N*19	H_2	24 hr., 850° C., A.C. and reheated 200° C. for 2½ hr.	22·8	42·4	67·4	82·2	25·0	6·8	...
	N_2		25·4	40·0	61·2	81·2	34·0	12·0	...
*N*19	H_2	24 hr., 850° C., A.C. and reheated 250° C. for 2½ hr.	...	...	67·0	86·4	30·0	10·6	...
	N_2		...	...	62·6	81·3	36·0	13·2	...
*N*19	H_2	24 hr., 850° C., A.C. and reheated 320° C. for 2½ hr.	24·9	41·5	66·2	84·7	36·0	12·7	...
	N_2		25·8	37·5	62·2	82·0	39·0	14·0	...
*N*38	H_2	24 hr., 850° C., A.C.	15·0	26·3	46·0	63·3	33·0	21·0	...
	N_2		16·0	26·4	45·4	80·0	57·0	29·0	...
*N*38	H_2	24 hr., 850° C., A.C. and reheated 100° C. for 3 hr.	16·0	29·2	46·0	76·4	50·0	23·5	1·25
	N_2		16·0	26·8	46·6	84·9	63·0	28·0	...
*N*22	H_2	24 hr., 850° C., A.C.	21·2	28·8	58·0	68·7	17·0	10·0	...
	N_2		21·6	28·6	58·0	83·9	38·0	18·6	...
*N*22	H_2	24 hr., 850° C., A.C., aged 45 days at R.T.	23·5	39·8	61·0	82·9	32·2	18·5	...
	N_2		22·0	30·5	61·0	83·4	35·0	19·0	...
*N*23	H_2	24 hr., 850° C., A.C.	36·0	58·0	72·4	72·4	nil	nil	...
	N_2		41·5	60·0	104·0	129·5	26·5	5·0	...
*N*23Mo	H_2	24 hr., 850° C., A.C.	30·5	48·0	72·0	96·0	25·0	3·1	...
	N_2		37·0	54·5	102·4	152·8	33·0	11·0	...
*V*30	H_2	24 hr., 850° C., A.C.	...	...	65·0	66·0	1·0	...	3·20
	N_2		...	...	72·8	101·0	44·5	14·0	...
*V*30	H_2	3 hr., 850° C., A.C.	...	...	77·1	88·8	16·5	9·0	1·78
	N_2		...	...	77·5	109·0	46·0	15·0	...
*V*30	H_2	½ hr., 850° C., A.C.	...	...	81·0	97·0	19·5	9·0	1·54
	N_2		...	...	81·0	117·2	50·0	15·0	...
*V*30	H_2	24 hr., 850° C., A.C., reheated 650° C. for 1 hr. and W.Q.	...	...	56·4	98·2	63·5	24·5	0·83
	N_2		...	...	57·0	98·7	65·0	23·0	...
*V*30	H_2	24 hr., 650° C., A.C.	...	...	50·5	79·4	49·5	20·0	0·53
	N_2		...	...	50·6	91·6	64·0	26·0	...
*V*30	H_2	24 hr., 650° C., W.Q.	...	...	51·0	80·0	49·5	20·0	1·75
	N_2		...	...	51·5	109·0	63·0	25·0	...
CM	H_2	24 hr., 850° C., A.C.	...	...	74·8	79·6	7·0	4·5	1·95
	N_2		...	...	72·8	122·7	56·0	18·0	...
*M*20	H_2	24 hr., 850° C., A.C.	...	...	27·0	50·4	52·0	36·0	1·92
	N_2		...	...	27·0	63·9	73·0	44·0	...
*K*6	H_2	24 hr., 850° C., A.C.	...	...	51·7	65·8	16·3	14·0	1·31
	N_2		...	...	51·5	73·0	35·5	21·0	...
*N*31	H_2	24 hr., 850° C., A.C.	46·0	49·5	84·0	87·8	9·0	3·1	...
	N_2		46·0	52·0	84·0	109·6	32·5	12·5	...

F.C. = Furnace-cooled. R.T. = Room temperature.

TABLE XXVI.—*Mechanical-Property Ratios for Hydrogen- and Nitrogen-Treated Steels.* (*For Analyses,* see *Table I.*)

Limit of Proportionality.		0·1% Proof Stress.		Maximum Stress.		Breaking Stress.		Reduction in Area.		Elongation.	
Steel.	Ratio.	Steel.	Ratio.	Steel.	Ratio.	Steel.	Ratio.	Steel.	Ratio.	Steel.	Ratio.
*N*21	0·40	*N*21	0·76	*N*23	0·70	*N*23	0·56	*N*23	0·00	*N*23	0·0
*S*69	0·52	*N*23Mo	0·88	*N*23Mo	0·70	*N*33	0·59	*V*30	0·02	*V*30	0·0
*N*37	0·65	*S*69	0·90	*N*19	0·86	*N*23Mo	0·63	*N*19	0·10	*N*19	0·05
*N*23Mo	0·82	*N*37	0·93	*V*30	0·89	*CM*	0·65	*CM*	0·13	*N*31	0·25
*N*19	0·86	*N*31	0·95	*N*21	0·99	*V*30	0·65	*N*31	0·28	*CM*	0·25
*N*23	0·87	*N*33	0·96	*M*20	1·00	*N*19	0·70	*N*22	0·45	*N*23Mo	0·28
*N*38	0·94	*N*23	0·97	*N*31	1·00	*M*20	0·79	*K*6	0·46	*N*22	0·54
*N*22	0·98	*N*19	0·97	*K*6	1·00	*N*38	0·79	*S*69	0·50	*K*6	0·67
*N*33	1·00	*N*38	1·00	*N*22	1·00	*N*31	0·80	*N*33	0·53	*N*21	0·71
*N*31	1·00	*N*22	1·01	*N*37	1·01	*N*21	0·81	*N*21	0·56	*N*33	0·71
...	...	...	...	*N*38	1·01	*N*22	0·82	*NV*	0·57	*N*38	0·72
...	...	...	...	*N*33	1·01	*NV*	0·87	*N*38	0·58	*NV*	0·78
...	...	...	...	*CM*	1·02	*K*6	0·90	*M*20	0·71	*S*69	0·82
...	...	...	...	*NV*	1·03	*N*37	0·92	*N*37	0·73	*M*20	0·82
...	...	...	...	*S*69	1·03	*S*69	1·08	*N*23Mo	0·76	*N*37	0·93

is almost unaffected by hydrogen, except in the cases of *N*23, *N*23Mo, *N*19, and *V*30, whilst the ratio between the breaking-stress results for hydrogen- and nitrogen-treated specimens shows a continuous gradual change from *N*23 to *S*69. For both reduction in area and elongation, the harmful effect of hydrogen is very marked in the cases of *N*23, *V*30, *N*19, and *CM*, and much less marked, though still prominent, for the other steels examined. It can therefore be said that, within the range of composition examined in the present work, excepting *N*23Mo, the effect of hydrogen upon the general mechanical properties is most pronounced in the case of the nickel–chromium, nickel–chromium–molybdenum, and chromium–molybdenum steels and that the nickel and plain carbon steels examined fall in quite another category.

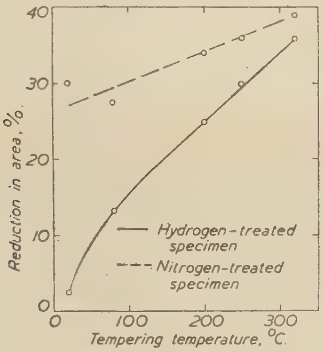


FIG. 48.—Effect of Tempering Temperature upon Reduction of Area of *N*19.

The miscellaneous experiments reported in Table XXV. show the effect of ageing at room temperature and of tempering after hydrogen treatment. In general, the mechanical properties are restored to normal by suitable ageing or temperature treatments, and the effect of tempering in the case of the chromium–molybdenum steel, *N*19, is illustrated in Fig. 48. As the tempering temperature is increased, the reduction of area for the hydrogen-treated specimen more closely approaches that of the nitrogen-treated specimen which has received the same tempering treatment. The effect of time of tempering at 105° C. upon the elongation and reduction of area of the case-hardening 3% nickel steel, *N*33, is illustrated in Fig. 49. It will be seen that 5 hr.

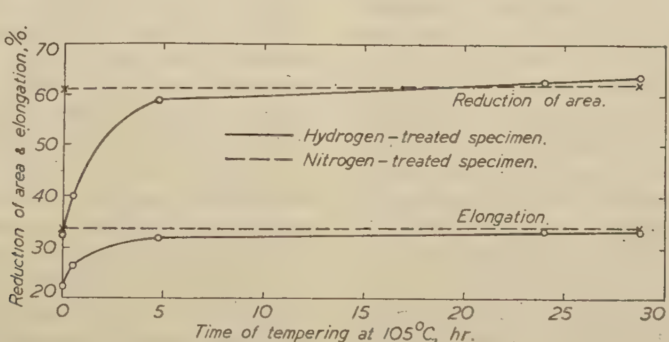


FIG. 49.—Effect of Tempering Time upon the Ductility of *N*33.

at this temperature is sufficient to restore the ductility of the steel practically to that of the nitrogen-treated specimen. The data given in Table XXV. for the nickel steel *N*21, which contains more carbon than does *N*33, show that in this case also, tempering at 135° C. for about 6 hr. is sufficient to restore the mechanical properties.

Discussion.

The primary object of this work was to investigate the removal of hydrogen from steel by heat-treatment, and results obtained by isothermal treatment of hydrogen-soaked specimens of nine different steels were reported in the first part of the paper (*see* Tables II. to XI., Figs. 1 to 9). As might be expected, the different steels showed different characteristics, although it is possible to group certain of them together according to their general behaviour. Thus, in each of the Figs. 1 to 9, there is an optimum temperature at which the removal of hydrogen from the corresponding steel can be most efficiently carried out. In the case of the 0·6% carbon steel, *K*6, and the case-hardening 3% nickel steel, *N*33, high rates of hydrogen removal under the standard conditions were observed over the wide temperature ranges of 150–700° C. and 200–650° C. respectively. For the other steels the optimum range is much more restricted, and with the 3% chromium–molybdenum steel, *CM*, there is a sharp peak at 725° C., corresponding to the pearlitic transformation of this steel. In addition, hydrogen removal is rapid from 200° to 400° C., but between this range and the upper optimum temperature there is a pronounced minimum in the hydrogen-removal curve. Similar characteristics are shown by the steels *FA*, *NV*, and *N*22, but the minimum centred round 550° C. is far less marked and covers a narrower range of temperature; also, as shown in Table XXVII., the removal of hydrogen from these steels is slightly more rapid in the intermediate than in the pearlitic range of transformation.

The behaviour of the nickel–chromium–molybdenum steel, *V*30, is similar to that of the nickel steel, *S*69, in that there is no optimum temperature in the upper range, and from 550° C. upwards there is a general increase in the rate of hydrogen removal with temperature, so that at 1100° C. the rate of removal of hydrogen is approximately the same as at the optimum intermediate temperature. The investigation upon the nickel–chromium–molybdenum steel, 4*S*11, was limited to the narrow temperature range 325–600° C. and, as shown in Fig. 1(*b*), there is a sharp peak on the hydrogen-removal curve at 450° C. Above this temperature the rate of hydrogen removal falls rapidly and at 600° C. only some 7·5% of the total hydrogen was removed during the 5-hr. isothermal treatment, the lowest removal ever recorded in this range.

The lack of precise isothermal-transformation data for these steels under the specified conditions does not permit an accurate correlation between hydrogen removal and transformation characteristics, but a review of the compositions of the steels indicates that in the majority of cases they do conform to each other. Thus, in steels which are known to transform both in the pearlitic and the intermediate range, such as the 3% chromium–molybdenum steel, *CM*, and the 1½% manganese–molybdenum steel, *FA*, there are two ranges of temperature in which the removal of hydrogen may be effectively carried out. For other steels, such as *V*30, where the transformation is not likely to occur within 5 hr. in the upper temperature range, only the intermediate temperature peak is observed on the hydrogen-removal curve. For comparison on this basis, the hydrogen-removal characteristics of the nine steels are grouped and summarized in Table XXVII.

Table XXVII.—*Optimum Temperature Ranges for Hydrogen Removal.*

Steel.	Temp., ° C.	H_2 Removed, %.
*K*6	150–700	86–94
*N*33	200–650	90–95
CM	725	86·6
	200–400	74–77
FA	625	90·0
	250–500	91–94
NV	600	88·5
	300–450	92–96
*N*22 (small specimens)	600	91·8
	250–450	88–97
*V*30	250–400	87·5–94·5
*S*69	300–450	83–89
4*S*11	450	87

Only four of the steels show a high rate of removal in the pearlitic range, and in only one case is this rate greater than that at lower temperatures. Furthermore, this upper range of temperature for rapid hydrogen removal is extremely narrow, whilst the lower region, which is observed in all steels, usually extends over a range of at least 150° C. From the point of view of hydrogen removal, at least from specimens of the size employed in this work, isothermal treatment in the intermediate range (usually at about 350° C.) is generally to be preferred to treatment at higher temperatures. On the other hand, when the pearlite transformation occurs at a sufficiently high temperature, as in the case of the 3% chromium–molybdenum steel, the resulting high rates of diffusion of hydrogen through the austenite and the transformation products may cause the rate of removal to be greater than at the lower temperatures.

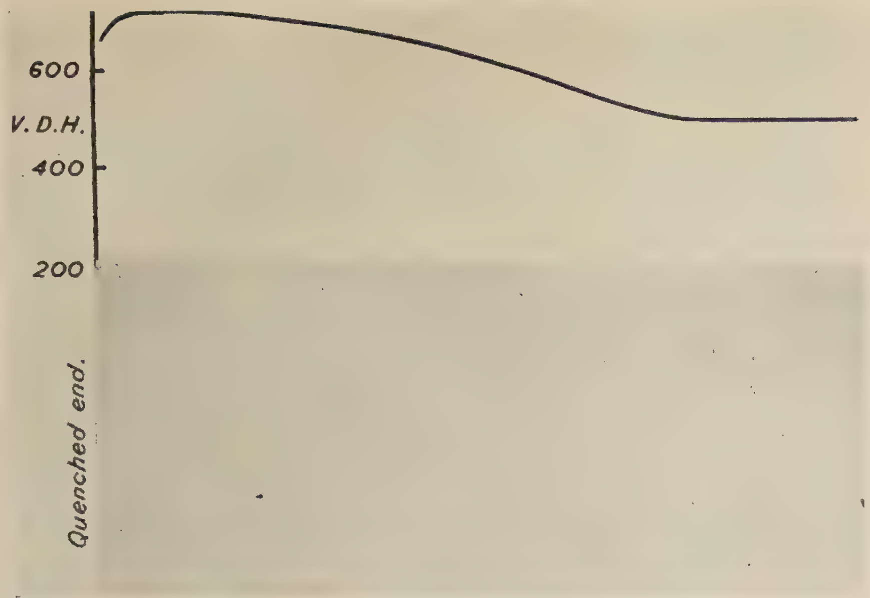


FIG. 50.—Steel *N*31.

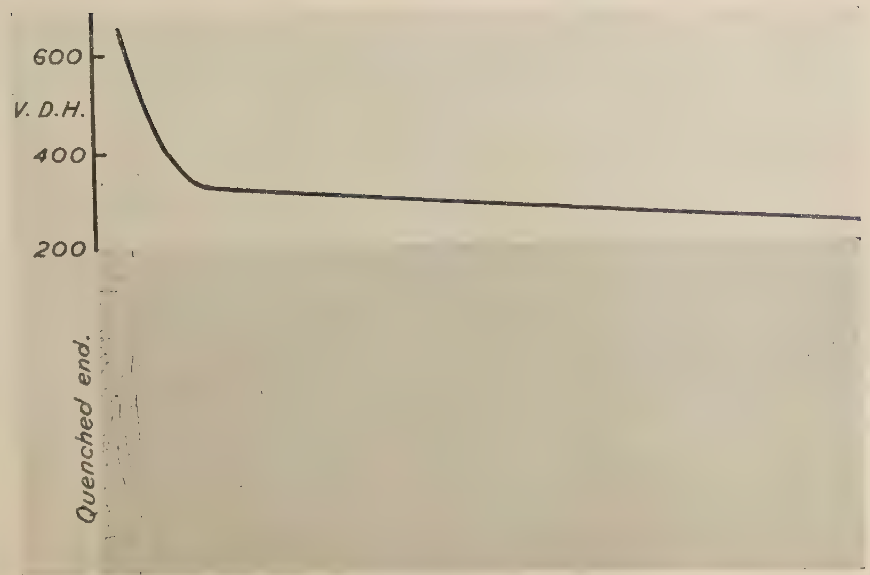


FIG. 51.—Steel *K*6.

FIGS. 50 and 51.—Crack Distribution and Hardness Curves for End-Quenched Specimens.

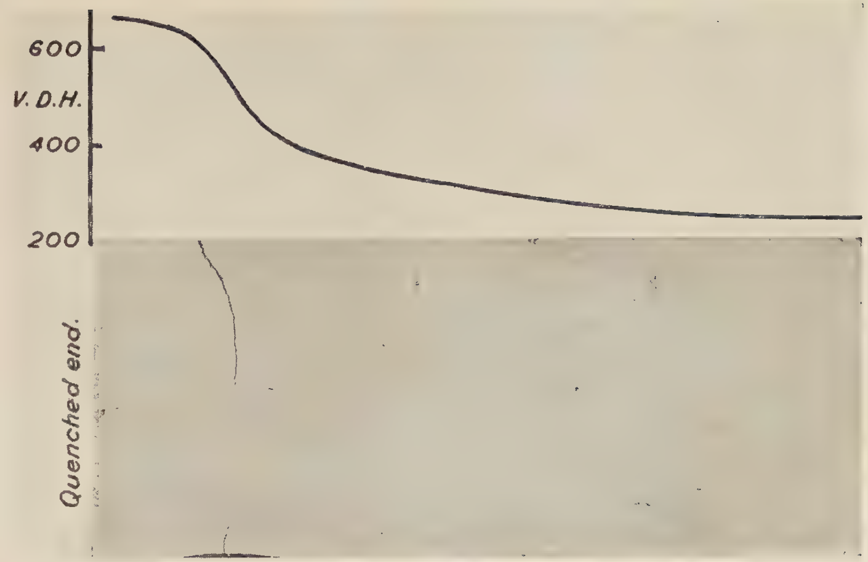


FIG. 52.—Steel *NV*.

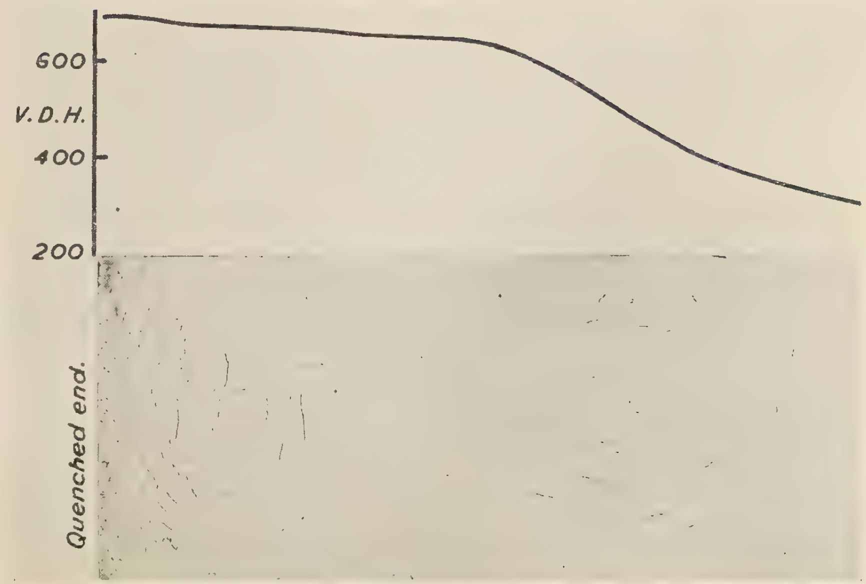


FIG. 53.—Steel *S*69.

FIGS. 52 and 53.—Crack Distribution and Hardness Curves for End-Quenched Specimens.

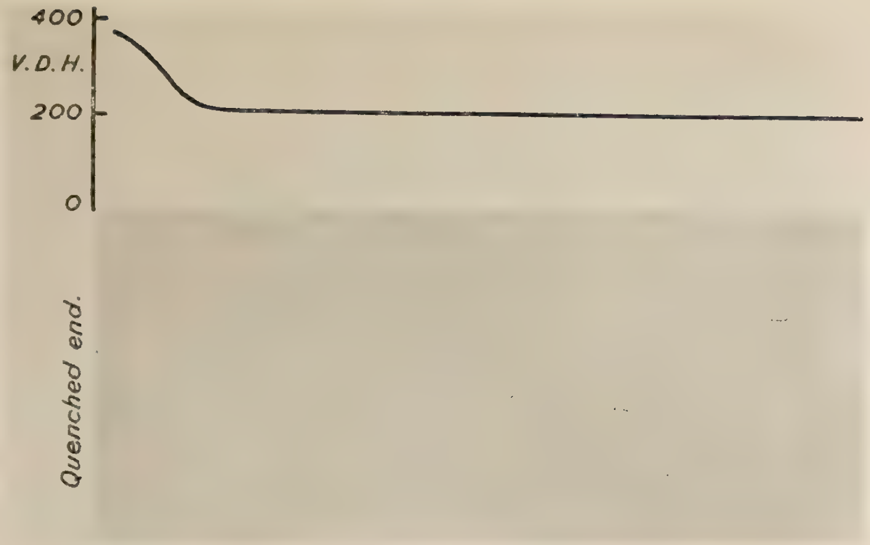


FIG. 54.– Steel *DB*.

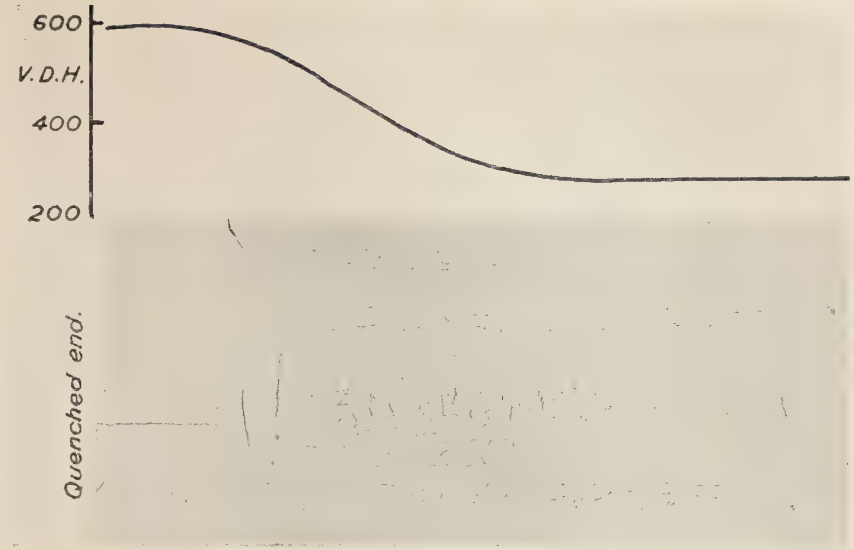


FIG. 56.—Steel *MM*.

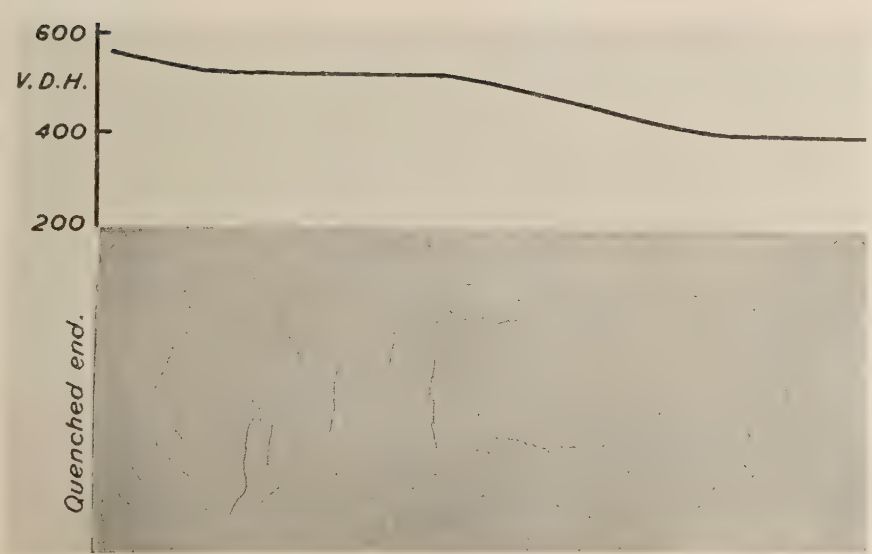


FIG. 55.—Steel *N*17.

FIGS. 54 and 55.—Crack Distribution and Hardness Curves for End-Quenched Specimens.

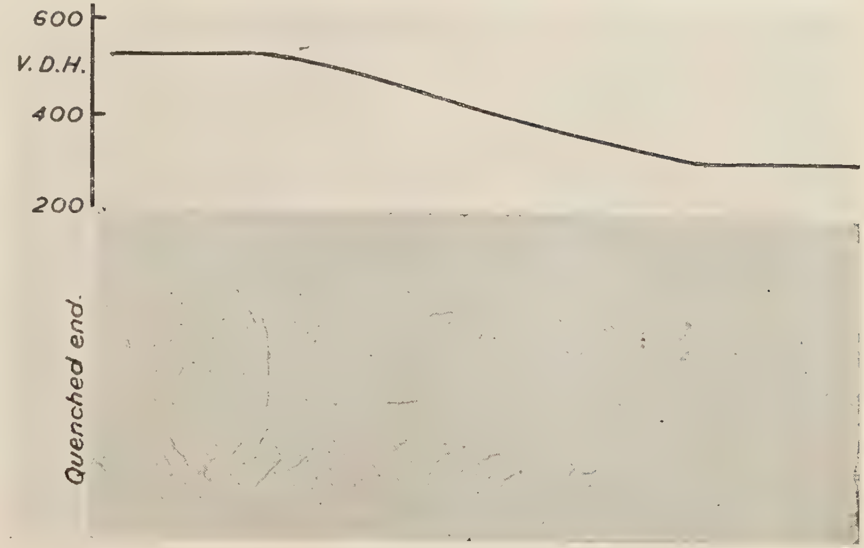


FIG. 57.—Steel *V*30.

FIGS. 56 and 57.—Crack Distribution and Hardness Curves for End-Quenched Specimens.

Isothermal treatment at 1100° C. was found to result in high rates of hydrogen removal from the steels *S*69, *V*30, *NV*, *K*6, *X*, *Q*, and *HD*, and it might be thought that a still higher temperature would be even better, particularly as all steels show an increasing rate of removal as the temperature is increased within the austenite range. This is contrary to industrial experience, and must be caused by the special conditions applying to the laboratory work. Thus, our specimens were free from scale and were surrounded by a dry nitrogen atmosphere throughout the isothermal treatment. Under industrial conditions, billets and forgings are heavily scaled and the furnace atmosphere is not entirely free from moisture or hydrogen. The experiments which have been carried out upon the effect of furnace atmosphere show that a very small partial pressure of hydrogen at such high temperatures considerably retards the removal of hydrogen from the steel. At lower temperatures the dissociation of steam and of molecular hydrogen is small and the retarding effect is reduced to negligible proportions, as shown by the experiments carried out at 650° C. Although further work is desirable, there are indications that the presence of scale also reduces the rate of removal of hydrogen.

The general shape of the hydrogen-removal curve gives a good indication of the difficulties of preventing crack formation in the corresponding steels. When a high rate of removal extends over a wide range of temperature, as with steels *K*6 and *N*33, a low susceptibility to hair-line crack formation is to be expected. To go to the other extreme, the very narrow and critical range of temperature in which hydrogen can be rapidly removed from 4*S*11 is in complete accord with the fact that this steel is very susceptible to hair-line cracks. Most of the steels examined were intermediate in behaviour between these two extremes, and in comparing them it is important to consider the general level of hydrogen removal over the whole temperature range. The curves for steels *FA* and *NV* show the same general tendencies, but the high rate of removal in the intermediate range is much more extensive for *FA* than for *NV*. On the other hand, the rate of removal from *FA* drops to 46% at 550° C., compared with 69% at 525° C. for *NV*. In both cases the 550° C. minimum is confined to a much narrower range of temperature than in the case of *CM*, for which removal is less than 50% between about 450° and 650° C. Moreover, the general level of hydrogen removal is much lower for *CM* than for any of the other steels examined except 4*S*11. It should be borne in mind that ease of hydrogen removal is not the only factor determining susceptibility to crack formation, for, as will be shown later, the concentration of hydrogen which may be present without crack formation varies considerably with the heat-treatment, even for a given steel.

The curves showing the hydrogen content of specimens given 5 hours' isothermal treatment bear an inverse relationship to the corresponding curves for hydrogen removal, in spite of the fact that the initial hydrogen content fluctuates considerably with temperature. These fluctuations must be attributed to the varying amounts of hydrogen lost during the first 10 min. in the isothermal bath, because experiments showed that the hydrogen content introduced by soaking for 24 hr. at 1100° C. was reproducible within narrow limits.

In the experiments so far considered, the time of isothermal treatment had been adjusted to the size of the specimen, in order that the residual hydrogen contents would reflect the characteristics of the steel. If the time of isothermal treatment had been sufficiently prolonged, the residual contents would have been negligible at all temperatures and would have given no indication of an optimum temperature. The results actually reported, using two specimens at each temperature, cannot be used directly as a quantitative guide for preventive heat-treatment under industrial conditions, unless the variation of hydrogen content with time and the probable effect of specimen size are also known.

Attempts were made to determine the law governing hydrogen removal using five specimens and various times of isothermal treatment. It was found that, at most temperatures, hydrogen removal was rapid in the early stages and slowed up as the residual hydrogen diminished. The experimental curves agreed reasonably well with an equation of the type :

$$y = \frac{K}{1 + a}(1 + ae^{-nt}),$$

where n varied with the temperature of isothermal treatment and a was a constant for a particular curve. By considering separately the radial and longitudinal diffusion of hydrogen in a cylinder, it was possible to develop an equation of this type for each case on theoretical grounds and to show that n must be related to D (the diffusion constant) and to l^2, where l is proportional to the linear dimensions of the specimen, so that $n = kD/l^2$. On the assumption that the value of n to be inserted in the empirical equation is also governed by this relationship, it is clear that the mass of the specimen and the rate of diffusion of hydrogen are the controlling factors in determining hydrogen removal from solid solution in a given steel. As far as mass is concerned, the experimental results given in Fig. 31 show that the time of heat-treatment necessary for similarly shaped specimens of the same steel

does increase with the square of the linear dimensions. Experiments on similar specimens of different steels and at the same temperature indicated that the value of n was the same in each case and could be regarded as characteristic of the temperature, and this could only be so if the diffusion constant for a given temperature was the same for all the steels examined. This was confirmed by experiments in which the rate of diffusion of hydrogen through steel was measured more directly, the results showing that a single curve related rate of diffusion with temperature for all steels in the austenitic condition, while another curve similarly applied to the α state. In all cases the rate of diffusion through α is greater than through γ at the same temperature. Further evidence for the close relationship between n and D was obtained when n was plotted against the absolute temperature T within the austenitic range. The general shape was similar to that of the D–T curve, and just as a linear relationship is known to exist between log D and $1/T$, so a straight line was obtained when log n was plotted against the reciprocal of the absolute temperature. There is good reason, therefore, for believing that the relationship which was found to agree with the results of laboratory experiments is of more general application, and that it affords a satisfactory basis on which to assess industrial heat-treatments.

Probably the least-understood feature of the empirical relationship is the limiting value which it imposes on the hydrogen content. As already stated, an empirical relationship may involve a limiting value because it is, in effect, an approximation, but it was shown that the theoretical treatment would lead to an equation in conformity with the experimental results only if such a limiting value was incorporated. For a given steel, the lower limit of the hydrogen content appears to increase as the temperature is lowered in the austenite range, and this is contrary to what might be expected if there had been a partial pressure of hydrogen on the outside of the specimen throughout the isothermal treatment. The only other possible explanation of the lower limit which can be seen at the moment is that there is some form of chemical linkage between the hydrogen and the steel, but there is little evidence to prove or disprove this view. Experiments to prove that there is a genuine lower limit to the hydrogen content are difficult to carry out. Thus, at high temperatures, the lower limit indicated by the equation is too small for a decisive experiment to be carried out; at temperatures such as 550° C., where the amount of hydrogen remaining after 5 hr. is large, prolonged treatment would lead to the transformation of the steel and this would have a complicating effect upon the hydrogen removal.

The treatment of the experimental results for the 3% chromium–molybdenum steel, *HD*, at 700° C. showed that the effect of transformation was to accelerate hydrogen removal from the steel. Similarly, the hydrogen-evolution curves obtained on cooling specimens of 4*S*11, *N*22, *FY*, and ingot iron, all indicated a pronounced evolution at the transformation. It may be significant that the maximum rate of evolution corresponds to the completion of transformation, as judged from the thermal curve, and it is conceivable that this is caused by concentration of hydrogen in the residual austenite. Indeed, as reported earlier in the paper, when the evolution specimen of 4*S*11 was reheated it was found that the steel evolved hydrogen while in the α state, but that as soon as austenite was formed *absorption* of gas took place.

Although it may be stated that, in general, the transformation accelerates the removal of hydrogen, whether it occurs at high or low temperature, the controlling difference in the two cases will be the diffusion constant. If the total time of heat-treatment is large compared with that necessary for transformation, the diffusion constant, D_α, for the α state is the controlling factor, and therefore the temperature of treatment should be as high as possible in order that D_α shall be as large as possible. It is not possible to generalize for shorter times of treatment, because the modes of transformation at the respective temperatures become important in determining the average diffusion constant prevailing throughout the time of heat-treatment. Thus, although the transformation of *FA* at 625° C. resembles that of *HD* at 700° C., the difference in the average diffusion constant during the 5-hr. isothermal treatment is such that for *FA* the maximum hydrogen removal is obtained at intermediate temperatures, whilst for *HD* the pearlitic range is most effective. For temperatures at which the transformation proceeds to completion in reasonable time, and for the larger masses encountered in industry which require such long times of treatment, the steel may be regarded as being in the α state throughout, and the average diffusion constant may be taken as D_α without introducing appreciable errors. The experimental curves, on the other hand, were obtained under conditions which did not justify this approximation and the average diffusion constant would be less than D_α in all cases. Hence the times of heat-treatment necessary for a given removal of hydrogen from large masses predicted from the experimental results will tend to be slightly too long.

Although but little laboratory work has been carried out on the effect of cooling to 300° C. followed by reheating to 650° C., this method is based on sound theoretical principles; the fact that the residual hydrogen content observed

in these experiments was the lowest ever recorded after 5 hours' treatment gives strong practical support to this kind of preventive heat-treatment.

The removal of hydrogen from steel is important from an industrial point of view, not only to prevent hair-line crack formation but also to ensure satisfactory mechanical properties. The tensile properties of a number of steels after hydrogen treatment have been studied, and it has been shown that hydrogen to the extent of 1–2 c.c./100 g. has a very injurious effect. As might be expected from the results reported by other workers for plain carbon steels, it was found that the elongation and reduction in area were the most affected and that the effect was most marked in the case of nickel–chromium–molybdenum and chromium–molybdenum steels. Hydrogen appears to reduce the limit of proportionality in most cases, although the 0·1% proof stress and the maximum stress are relatively unaffected. Normal mechanical properties may be restored by ageing the tensile test-piece at room temperature for a sufficient length of time, or, more rapidly, by tempering at an elevated temperature. Such easy removal of hydrogen will not be possible for larger masses, and although, for example, 5 hr. at 105° C. was found to be sufficient to restore the mechanical properties of *N*33, the time necessary for larger masses will increase with the square of the linear dimensions. It will be recalled that the hydrogen contents of the tensile specimens which showed embrittlement were considerably lower than those generally associated with hair-line crack formation, and that the greatest difficulty is encountered in removing the last 1 or 2 c.c./100 g. of hydrogen from the steel.

The work on hydrogen removal has revealed much additional evidence concerning crack formation; generally speaking, the severity of cracking is in agreement with the hydrogen content of the specimen, and most of the results fit in with the views expressed in a previous paper.[1] The theory then put forward involved the retention of a hydrogen-rich constituent, probably austenite, where cooling through the transformation was rapid, and on this basis it could reasonably be expected that hydrogen would exert some influence upon the transformation. Work carried out on isothermal transformation of the nickel–chromium–molybdenum steel, 4*S*11, showed that hydrogen retarded transformation above 450° C., with a maximum effect at 550° C. Below 450° C. a slight effect only was detected, and this appeared to be in the nature of an acceleration. In keeping with this, the only steel examined which showed an effect due to hydrogen in the standard Jominy end-quench test was *N*22, which would transform at 570° C. on air-cooling. Other steels transforming on air-cooling at about 400–450° C. showed no difference in hardness between hydrogen- and nitrogen-treated specimens. Dilatation specimens treated in hydrogen showed some 20–30% less expansion than the nitrogen-treated control specimens at the $\gamma \longrightarrow \alpha$ transformation, but, although this effect could be explained in terms of the retention of austenite by hydrogen, it could be due to the expansion of the γ lattice by hydrogen being greater than that of the α lattice.

Much of the criticism advanced against an earlier paper[1] was to the effect that the radial cracks observed in quenched specimens were of different origin from the deep-seated random cracks encountered in industry, but the isothermal work on the nickel–chromium–molybdenum steel, 4*S*11, showed that it was possible to obtain deep-seated random cracks in small specimens. Specimens completely untransformed in the isothermal bath before quenching in water showed radial cracks, those which were completely transformed before quenching contained deep-seated random cracks, while those in which partial transformation had occurred gave a mixture of radial and random cracks. This was also true of the other steels for which the isothermal removal of hydrogen was investigated, except that in the case of *CM* no random cracks were obtained. As shown in Fig. 44, none of the 4*S*11 specimens transformed at 600° or 550° C., whereas most of those held at 350° and 250° C. were completely transformed before quenching in brine. For all these temperatures cracks were observed, or not, according to the time of isothermal treatment, which would determine the hydrogen content of the specimen at the time of quenching. The results in the intermediate range show that, given a sufficiently high hydrogen content, cracks may be produced in the absence of transformation stresses. Further, the results at 550° and 600° C. show that transformation stresses do not cause internal cracks in the absence of hydrogen. It would seem, therefore, that the importance of existing stresses is mainly in determining the distribution of cracks.

The fact that hydrogen is essential to hair-line crack formation is amply confirmed by the specimens used to determine the law of hydrogen removal at various temperatures, particularly in the austenitic range. In all cases, the number of cracks was in accord with the hydrogen content; the higher the hydrogen content the more numerous were the cracks. In general, this also applies to the pairs of specimens used in dedetermining the removal of hydrogen under isothermal conditions, but certain anomalies occur, which have been tabulated in Table XXVIII. Steels 4*S*11, *FA*, and *V*30 gave no anomalous results, but for each of the other steels there appear to be certain temperature ranges in which crack formation does not take place, although

the hydrogen content is high. Thus, no cracks occur in the range 150–200° C. for the steel *S*69, or in the range 350–400° C. for *CM*, but the other three steels, *NV*, *N*33, and *K*6, have two such ranges.

A number of wrong conclusions were drawn from early experiments on steel containing hydrogen, because it was not known that an incubation period was necessary for crack formation. If specimens were sectioned within this period, no indication was obtained of the cracks which would have developed on more prolonged ageing. Our general experience had shown that with the standard size of specimen, ageing for a week at room temperature was sufficient to ensure crack formation before reheating for the hydrogen determination, but the possibility arises that with certain forms of isothermal treatment the incubation period might be considerably lengthened and the steel might be in such a state as to permit relatively slow reheating to 650° C. without crack formation. The temperature ranges in which no cracks were obtained were least critical in the case of the tyre steel, *K*6, and on several occasions specimens of this steel were soaked in hydrogen, quenched to 400° C. for 10 min. and then quenched in brine. The specimens were held at room temperature for varying periods up to 2 months and were then heated for the hydrogen determination, sectioned, and examined for cracks. In no case were cracks observed, and during the period of ageing something like 90% of the total hydrogen content was evolved at room temperature. The conclusion must be drawn, therefore, that cracks do not occur in *K*6 specimens of standard size which have been given an isothermal treatment at 400° C., in spite of a high hydrogen content. This excludes the possibility that incubation has a special character in specimens which have been treated in these apparently "immune" ranges of temperature.

Table XXVIII.—*Examples of Anomalous Hair-Line Crack Formation Observed in Isothermal Work.*

Steel.	Isothermal Treatment. Temp., ° C.	Isothermal Treatment. Time.	H_2 Content, c.c./100 g.	Description of Cracks.
*4S*11	No anomalies observed over complete range.			
FA				
*V*30				
NV	500	10 min.	5·24	No cracks, but many pits.
	250	10 ,,	5·06	
	525	5 hr.	1·67	Several fine, deep-seated cracks.
*S*69	200	10 min.	5·77	No internal cracks.
	150	10 ,,	6·11	No cracks.
	100	10 ,,	5·92	Many fine, small, and medium cracks.
	500	5 hr.	2·07	20–30 deep-seated, random cracks.
CM	400	10 min.	6·03	No cracks.
	350	10 ,,	6·11	
	600	5 hr.	3·74	8 radial cracks (all cracks observed in this steel were radial).
*N*33	650	10 min.	5·24	No cracks.
	300	10 ,,	5·67	
	250	10 ,,	5·55	
	400	10 ,,	4·83	10 or more, random, deep-seated cracks.
*K*6	650	10 min.	3·75	No cracks.
	600	10 ,,	4·60	
	550	10 ,,	3·51	
	400	10 ,,	7·02	
	350	10 ,,	6·21	
	300	10 ,,	4·92	
	250	10 ,,	5·21	
	200	10 ,,	5·33	
	150	10 ,,	6·27	
	750	5 hr.	2·36	6 deep-seated, random cracks.
	725	5 ,,	2·83	

In Table XXVIII. there appears to be no correlation between the structure of the steel and the lack of cracks, the best example being *K*6, in which no cracks were observed in specimens possessing structures ranging from ferrite and pearlite to martensite.

Further evidence that cracks do not occur in certain steels of high hydrogen content when the transformation occurs at certain temperatures, was obtained when specimens of different steels

2 in. in dia. and 4 in. long were soaked in hydrogen at 1100° C. and given an end-quench on a Jominy apparatus. The most outstanding effect was that observed in the case of the ball-bearing steel, *N*31, in which no cracks were observed near the quenched end, where the diamond pyramid hardness was about 700, whilst the upper half of the specimen, with a hardness number ranging from 500 to 600, contained numerous cracks. It will be recalled that in a separate experiment it was shown that no cracks occurred in water-quenched specimens of *N*31 containing hydrogen to the extent of 7·43 c.c./100 g., although numerous cracks were found in the corresponding air-cooled specimen for which the hydrogen content was only 4·64 c.c./100 g.

In *K*6 the cracks were confined to a narrow zone at the quenched end, but in most other specimens the cracks were more widely distributed throughout the specimen, although each steel showed at least one zone in which cracks were absent or fewer than in the surrounding regions. The position of this "crack-free" zone varied from steel to steel and corresponded to different rates of cooling. The most noticeable crack-free zone occurred in *S*69, in the middle third of the specimen, separating two distinct zones with quite different crack distributions. The hardness of the crack-free zone ranged from 560 to 640, which would be compatible with the transformation occurring in the 150–200° C. range, which was found to be an "immune" range for this steel in the isothermal treatment. Although the different steels gave characteristic crack distributions, steels of almost the same composition, such as *MM* and *N*17, behaved very differently. Very few cracks were observed near the quenched end of *MM*, whilst the corresponding region in *N*17 contained many long cracks. On the other hand, steels of widely differing compositions, such as *DB* and *NV*, behaved similarly as far as cracks were concerned.

In an attempt to explain these additional facts in terms of the theory advanced in the previous paper,[1] it might be said, for example, that more austenite was retained on air-cooling than on water-quenching the 1% chromium, 1% carbon steel, *N*31, but even on this basis it is difficult to explain the entire absence of cracks from the quenched steel. Some austenite would be retained on quenching, and the hydrogen content was certainly greater than in the air-cooled specimen.

It is clear from the effect of hydrogen upon the mechanical properties of low-alloy steels that the earlier theory must be modified to take account of the fact that the hydrogen necessary for crack formation is more than sufficient to cause embrittlement. It might be thought that a combination of transformation and other stresses with hydrogen embrittlement would satisfactorily account for the observed results, but this is clearly not so. Thus in the case of *N*31 the crack-free specimen has a higher hydrogen content and is in a more highly stressed condition than the air-cooled specimen, which contained numerous cracks.

Since the most anomalous results were observed in the case of two steels of high carbon content, *N*31 and *K*6, on the one hand, and with *N*33 of low carbon content on the other, it seems reasonable to try to explain the anomalies in terms of the possible effects of carbon. One possibility is that, owing to the high carbon content, the lattice would be in a more expanded state and would be able to accommodate more hydrogen without disrupting the steel. It is true that most of the hydrogen contained in *N*31 is not evolved unless the specimen is heated, but *K*6 in the hardened condition gives off most of its hydrogen at room temperature. In this respect the tyre steel, *K*6, behaves like the low-carbon nickel steel, *N*33. Similarly, these results cannot readily be explained in terms of a possible effect of carbon upon the rate of diffusion of hydrogen through the steel.

Owing to the considerable differences in composition of the steels examined, it is difficult to see any systematic variations in behaviour with respect to crack formation. It is interesting, however, to compare the results obtained for the two nickel steels, *S*69 and *N*33, which have carbon contents of 0·44 and 0·15% respectively. *S*69 shows an "immune" range at 150–200° C., while *N*33 shows a much wider one between 150° and 300° C., as well as another between 450° and 650° C. The lower range may be regarded as common to both steels, and comparison of the hydrogen contents observed for the specimens held for 10 min. in the isothermal bath indicates that hydrogen escapes much more readily from *N*33 than from *S*69 in this range of temperature. These observations, and the rest of the results obtained for *S*69 and *N*33, justify the conclusion that in nickel steels of approximately the same alloy content, the behaviour with regard to crack formation and hydrogen retention is determined largely by the carbon content.

Although most of the steels examined have approximately the same carbon content of about 0·3%, it is not possible to assess the influence of the different alloying elements, owing to the complex combinations involved.

It may be helpful to consider in what way the earlier theory should be modified in the light of these new results. There is still no evidence of the formation of internal cracks in the absence of hydrogen, but in certain cases hydrogen may be present to the extent of 6·0 c.c./100 g. without giving rise to crack formation. Two effects of hydrogen must be taken into account: (1) Em-

brittlement, which apparently occurs in most low-alloy steels with hydrogen contents of 1–3 c.c./100 g., and (2) the development of pressures within internal cavities when atomic hydrogen diffuses into them and is converted into molecular form in an attempt to build up the equilibrium pressure. It does not seem to be generally realized that, owing to the square-root pressure law which governs gaseous solubility in metals, if a sample of steel contains hydrogen to the extent of X c.c./100 g., when its solubility corresponding to one atmosphere is Y c.c./100 g., it will try to build up the equilibrium pressure P given by :

$$P = X^2/Y^2 \text{ atmospheres.}$$

If the hydrogen is unable to escape from the steel, this pressure will inevitably be reached in any internal space or cavity capable of holding a few molecules of hydrogen. Thus, consider a steel sample containing hydrogen to the extent of 5 c.c./100 g. at room temperature (where the solubility of hydrogen at one atmosphere partial pressure is certainly not more than 0·05 c.c./100 g.); the equilibrium pressure which would be developed in internal cavities is about 70 tons/sq. in. Taking into account the brittle nature of the steel containing hydrogen, an internal pressure of this order would, to say the least, be extremely undesirable.

The building-up of pressures within internal cavities will not satisfactorily explain all the phenomena involved in this and earlier work, although we believe that the pressure effect must play a part at the time of crack formation. Moreover, the crack-free zone observed near the surface of billets is most readily explained by the fact that hydrogen escapes from the surface, and the reduced concentration in the vicinity causes the equilibrium pressure to be correspondingly reduced. The sudden evolution which has been observed to accompany crack formation in certain steels cannot be explained in terms of hydrogen in solid solution, and the idea that a hydrogen-rich constituent was retained to room temperature was put forward in an earlier paper.[1] In the discussion of that paper it was further stated that this constituent was probably austenite which had been stabilized by the hydrogen concentrated within it, but this view does not give a satisfactory picture of all the results now available. Although the idea of a hydrogen-rich constituent still seems to be necessary, it is likely that, under certain circumstances at least, the constituent may be a transformation product, and it is possible that there is a close linkage between the hydrogen and the carbon and other elements in the steel. It is possible that the limiting hydrogen content is of real significance and that it is due to some such linkage as this, particularly as its value in the austenitic range diminished with increasing temperature.

If linkage exists between hydrogen and the carbon and other elements in the steel, it can no longer be regarded as being in solid solution, and under certain circumstances it may be that the hydrogen could be retained in the " bound " form indefinitely without crack formation resulting. The behaviour of $N31$ could be explained on some such hypothesis, provided that quenching increased the stability of the linkage.

Owing to the complex nature of the problem, it is not possible to give more details of the properties which such a hydrogen constituent must possess, or to specify more closely the conditions under which it is likely to be formed. On the assumption that carbon plays an important part in the constituent, it is likely that any alloying element which affects the state of the carbon in the steel will also effect the behaviour of the steel with respect to hydrogen. Similarly, the effect of the temperature of treatment upon the state of the carbon would be reflected in the behaviour with regard to formation of the hydrogen constituent. The temperature of treatment will also determine the structure of the steel, and it is likely that the diffusion constant at room temperature will vary accordingly. The value of the diffusion constant seems to be of considerable importance, particularly from the point of view of hydrogen pressure, but the evolution of hydrogen from steel will be determined by any affinity which the steel may have for hydrogen as well as by the diffusion constant. Thus a large amount of hydrogen may be evolved at room temperature when the diffusion constant is small if there is a pronounced lack of affinity, or there may be little evolution from a steel for which the diffusion constant is large, because the hydrogen is held in some form other than solid solution. It is probable that of the two effects, the value of the diffusion constant is less important in governing crack formation. It is possible for approximately the same amount of hydrogen to be given off in a week at room temperature from two specimens of the same steel, and cracks may occur in one case and not in the other, although the temperature of isothermal treatment in the two cases differs by only 50° C. and the total hydrogen contents are comparable. For example, specimens of $K6$ isothermally treated at 400° C. for 10 min. give no cracks, although the hydrogen content is 7·02 c.c./100 g. and the evolution curve at room temperature is a smooth curve with diminishing rate corresponding to hydrogen in solid solution. On the other hand, similar specimens isothermally treated at 450° C. for 10 min., although containing only 5·35 c.c./100 g. contained nine radial cracks. The evolution curve at room temperature for this specimen differed from that for the specimen treated at 400° C. in that, although the initial evolution

rate was approximately the same, there was a marked inflection after about 3 days, so that after a week the rate of evolution was more rapid than from the 400° C. specimen. This type of behaviour was observed in earlier work, and was attributed to the breakdown of a hydrogen-rich constituent.

The present position with regard to hair-line crack formation may be summed up as follows :

(i) Hydrogen is essential to hair-line crack formation.

(ii) The presence of hydrogen causes (*a*) embrittlement, and (*b*) pressure to be built up within internal cavities.

(iii) Hair-line cracks may occur in the absence of transformation stresses.

(iv) A simple hydrogen-pressure or hydrogen-embrittlement theory will not explain all the known facts.

(v) The facts which cannot be explained in terms of hydrogen pressure being built up within hydrogen-embrittled material are in keeping with the formation of a hydrogen-rich constituent, which is not necessarily austenitic in nature. The conditions of formation and the detailed behaviour of this constituent cannot be given at this stage.

A full explanation of hair-line crack formation cannot be available until the effects of various alloying elements upon steel under various conditions are thoroughly understood. It would seem that the most logical form of attack upon the hair-line crack problem would consist of a much wider investigation of low-alloy steels in general.

Acknowledgments.

The authors wish to thank their colleagues for the helpful interest which they have taken in this work. They also wish to express their gratitude to the Members of the Hair-Line Crack Sub-Committee, who have helped by the provision of suitable steels and in other material ways, and to the Sub-Committee as a body for their stimulating and constructive criticism during the course of this work. The views expressed in this paper are those of the authors, and should not be taken as necessarily endorsed by the Sub-Committee as a whole.

REFERENCES.

1. Andrew, Bose, Lee and Quarrell : *Journal of The Iron and Steel Institute*, 1942, No. II., pp. 203 P–243 P.
2. Barrer : "Diffusion in and Through Solids." London, 1941 : Cambridge University Press.
3. Austin and Rickett : *Transactions of the American Institute of Mining and Metallurgical Engineers*, 1939, vol. 135, p. 396.
4. Zapffe and Sims : *Transactions of the American Institute of Mining and Metallurgical Engineers*, 1941, vol. 145, p. 225.

A LABORATORY INVESTIGATION OF THE PHOSPHORUS REACTION IN THE BASIC STEELMAKING PROCESS.*

By K. BALAJIVA, B.Met., Ph.D., A. G. QUARRELL, D.Sc., F.Inst.P., F.I.M., and P. VAJRAGUPTA, Ph.D., A.R.S.M. (University of Sheffield).

Paper No. 34/1946 *of the Ingot Committee.*

(Figs. 4 to 16 = Plates V. and VI.)

Synopsis.

A new technique, developed for melting slags and metal together at controlled temperatures and for taking satisfactory samples of slag and metal, is described. The technique has been applied to a study of the phosphorus reaction at 1585° *C., using prefused slags containing all the normal constituents except* CaF_2*, but with a much wider range of composition than is normally encountered in industry. It is shown that the empirical relationships which have previously been developed for purposes of industrial slag control break down when applied to slags having a wide range of compositions. On the other hand, a linear relationship is found to exist between the logarithm of the phosphorus equilibrium constant* ($k = P_2O_5)/[P]^2(FeO)^5$ *and the logarithm of the total lime content of the slag. On the basis of this relationship, curves are drawn to assist in slag control at* 1585° *C.*

X-ray and petrographic examinations of the slags have been carried out and three constituents have been identified: (i) *A solid solution of* $3CaO.P_2O_5$ *in* $2CaO.SiO_2$, (ii) $2CaO.Fe_2O_3$*, possibly in solid solution with* $4CaO.Al_2O_3.Fe_2O_3$*, and* (iii) *an oxide phase consisting mainly of FeO, MgO, and MnO in solid solution. The free-lime contents of the various slags are calculated on the basis of* $3CaO.P_2O_5$ *and* $2CaO.SiO_2$ *and various assumptions with regard to* Fe_2O_3 *and* Al_2O_3*, and the correlation between log (free lime) and log* k *are determined statistically. Of the assumptions made, that in which* Al_2O_3 *was ignored and each molecule of* Fe_2O_3 *required* 0·75 *molecules of CaO was found to give the best result, subject to the limitations involved.*

The results of this preliminary investigation indicate that the new technique should be applicable to a wide range of slag–metal problems involved in the steelmaking process.

Introduction.

The slag–metal reactions involved in steelmaking have been investigated by methods which fall into two main groups. In the first and most obvious method, samples of slag and metal are taken from industrial furnaces; such investigations are necessarily limited, however, to certain ranges of slag composition, as the economic factor demands that the finished steel shall be of usable quality. Moreover, until the development of the quick-immersion couple, there has been no really satisfactory means of measuring the bath temperature.

The second group consists of investigations carried out under laboratory conditions, and the practical problems in this case are even greater. The small scale upon which such experiments are usually carried out makes very high demands upon the refractory employed and renders temperature control difficult. German workers have generally employed crucibles of alumina, beryllia, or zirconia, heated in a Tammann furnace, and have claimed that it is possible to heat slag and metal together in such crucibles at a steady temperature and without appreciable contamination of the slag. The times for which the slag and metal have been maintained in contact at melting temperature have been small, and may have been insufficient for the attainment of equilibrium conditions.

A summary [1] of the methods employed in America appeared in 1940. By using a rotating-

* Received August 13, 1945. This paper is published by authority of the Ingot Committee. The views expressed in it are the authors' and are not necessarily endorsed by the Committee as a body.

liquid-iron crucible so that the slag does not come into contact with the refractory, Barrett and others claim to have overcome the main difficulties of laboratory work. Slags which wet the surface of the metal tend to climb out of the rotating-liquid-metal crucible and to come into contact with the refractory, and the advantages of the method are therefore not available in such cases.

In the same paper Jette and Chipman described high-frequency furnaces with stationary crucibles, used for the investigation of slag–metal reactions. In such furnaces there is a tendency for the slag to be much colder than the metal; in order to minimize this effect a graphite disc is supported just above the slag surface, to heat it by radiation.

As far as this country is concerned, there appears to have been no work carried out on slag–metal reactions on the laboratory scale, and the objects of the present investigations were to develop a suitable technique and then to apply it to a study of the phosphorus reaction in the basic steelmaking process.

Development of Experimental Technique.

After a review had been made of the resources available when this work was undertaken, it was decided to carry out experiments with a molybdenum-wound furnace and refractory crucibles. Such an arrangement has the advantage that a fairly large uniform-temperature zone is possible and temperature measurement is not difficult. Beryllia and zirconia crucibles were not obtainable at the time, but there was reason to believe that a satisfactory crucible could be made by bonding electrically fused magnesia with 5% of titania and firing at a sufficiently high temperature. It was found, however, that, although such crucibles were extremely dense, the slag soaked into the refractory when slag and metal were melted together, and it was not possible to maintain a layer of liquid slag above the metal. Other available refractories were tried, but in all cases the results were unsatisfactory. It became obvious that the chief cause of failure in this experimental arrangement was that the outside of the crucible was hotter than the inside, so that the temperature gradient favoured slag penetration of the refractory.

In view of this, it was decided to build small experimental furnaces in which the temperature gradient through the refractory would be such as to minimize slag penetration. Two different types were built, one a gas-fired open-hearth furnace with high-pressure blast and no preheating, and the other a small electric-arc furnace. With the open-hearth furnace it was found that the time taken to reach steelmaking temperatures was so great that the refractory became heated throughout, and it was not possible to maintain a layer of slag over the molten steel because as soon as further additions of slag were melted they were absorbed by the refractory.

The small arc furnace proved satisfactory from the point of view of slag penetration, and, although temperature control was difficult, the results were sufficiently promising to justify further work on these lines. The hearth was prepared by ramming a fused magnesia lining into a cavity made in a framework of chrome-magnesite bricks. The roof and side walls were also made of chrome-magnesite bricks, as it was found that silica and sillimanite would not withstand the intense heat of the arc at such short distances. Graphite electrodes $1\frac{1}{4}$ in. in dia. were introduced through suitable openings in the side walls and were mounted in holders with an adequate range of adjustment in a number of directions.

The small size of the furnace and the fact that a continuous temperature record was required precluded the use of the quick-immersion couple, and it was decided to introduce a thermocouple sheath through the side of the hearth and below the slag–metal interface. Sheaths were made of finely ball-milled electrically fused magnesia bonded with 5% of titania. Although the platinum/platinum–13% rhodium couple would sometimes last for the duration of the heat, on many occasions failure occurred almost as soon as slag and metal were melted in the hearth. In certain cases it was clear that the failure was due to slag attack upon the magnesia sheath, for, although the sheath was below the slag–metal interface, surface-tension effects caused the slag to creep down between the metal and the hearth wall and to come into contact with the sheath. Various shapes of hearth were used in an attempt to overcome this difficulty, and the shape shown in Fig. 1 finally solved the problem.

Failure of the thermocouple still occurred from time to time, but in such a manner that it was clear that slag attack was not responsible. The solution of this trouble was found when a carbon monoxide flame was observed burning at the open end of the thermocouple sheath, which suggested that oxidation of the carbon in the pig iron was resulting in the formation of carbon monoxide, some of which was diffusing through the magnesia sheath to the thermocouple. At that time electrically fused alumina insulating sleeves were not available for the thermocouple, and those in use had been prepared from alumina cement containing a small proportion of silica. When the carbon content of the bath was reduced, no further trouble was experienced in temperature measurement.

Temperature control was carried out by means of a manually operated variable choke in the secondary of the welding transformer used to supply the arc current. The accuracy of control

depended to a large extent upon the speed of response of the temperature indicator, as well as upon the experience and skill of the operator. In the first experiments a portable potentiometer was employed, and it was necessary for verbal indication to be given of any change in temperature. This caused some time-lag, and control was not as good as was required. The use of a Carpenter-Stansfield deflection potentiometer enabled the person operating the variable choke to observe the temperature fluctuations as and when they occurred, and under these conditions it was found possible to maintain the temperature at any required value to within $\pm 10°$ C., provided that the slag was not unduly viscous. At a later stage a Tinsley D.C. amplifier with recorder and large dial indicator was installed, and the results were equally satisfactory.

It was found convenient to use suitably sized pieces of steel for the cold charge, and no difficulty was experienced in melting. Appreciable oxidation occurred during the melting-down stage, however, and since this would make accurate control of slag composition difficult, it was decided to maintain an atmosphere of commercial nitrogen in the furnace. The nitrogen was fed in through holes in the roof of the furnace, and the joints between the different layers of brick were made more or less gas-tight by means of asbestos packing. Easy access of air through the electrode ports was prevented by fitting self-adjusting doors of asbestos.

The addition of slag to the melt presented some difficulty. It was desired to use slags made up from pure chemicals, and the first method employed consisted of mixing suitable chemicals in the required proportions by prolonged ball-milling and then adding the mixed powder to the melt. The arc tended to blow the powder out of the furnace, and the differing densities of the powders caused variations in composition. Moreover, the bulk of the powder was so great that the time taken in adding the required amount of slag was much too long. The mixed powders were therefore compressed into pellets of convenient size, but the bulk was still too large and the melting time was unduly prolonged. The addition of lumps of industrial slag was found to be quite satisfactory, and therefore it was decided to prefuse the chemicals in a small auxiliary arc-furnace. This procedure is described in detail later, and was used throughout this work.

No difficulty was experienced in obtaining satisfactory samples of slag and metal. A clean copper block was dipped into the slag and immediately quenched in clean cold water. A layer of chilled slag about $\frac{1}{8}$ in. thick adhered to the copper block, and the rate of cooling was extremely rapid. Immediately after the slag sample had thus been taken, a rapidly cooled pencil of the metal was obtained by means of the apparatus devised by Taylor and Chipman.[2] In this sampling device the molten metal is sucked by means of an aspirator bulb into a tapered cavity in a copper cylinder. The sample was rapidly quenched in water as soon as it had been taken; the sampling apparatus is described in more detail under a separate sub-heading.

Apparatus and Experimental Procedure.

Furnace Assembly.

The furnace assembly finally adopted is shown in Fig. 1, and consisted of three layers of chrome-

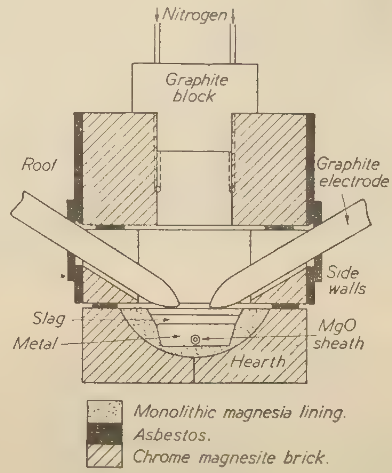


Fig. 1.—Section of Experimental Furnace.

magnesite bricks, cut to shape, held together in steel clamps. Further details of the roof and side-wall layers are given in plan in Fig. 2; the

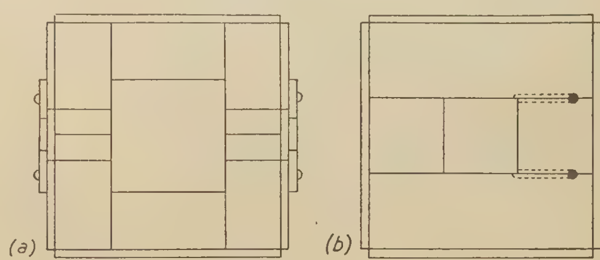


Fig. 2.—Plans for (*a*) Furnace Side-Walls and (*b*) Roof.

construction of the hearth can best be understood by reference to Figs. 5 and 6.

Electrical Circuit.

The circuit employed is shown diagrammatically in Fig. 3 and a general view of the apparatus is given in Fig. 4. A Ferranti 110-V., 16·5-kVA., oil-cooled welding transformer was used to supply the arc current, which was limited by means of oil-cooled fixed and variable chokes in

the secondary circuit. The variable choke was of such a capacity that when the arc was running normally, with slag and metal properly melted, it was possible to adjust the current within the range 40–200 amp. The core of the choke could

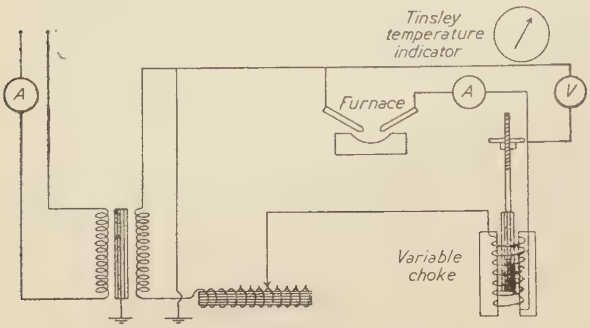


FIG. 3.—Electrical Circuit.

be raised and lowered by means of a hand-wheel and screw, which gave smooth and continuous adjustment, and this facilitated temperature control. For convenience in control, ammeters and voltmeters were incorporated at suitable points in the circuit.

Preparation of Hearth.

The hearth cavity in the chrome-magnesite bricks was dish-shaped and approximately 6 in. in dia. at the top, with a maximum depth of 2 in. Finely ball-milled electrically fused magnesia was bonded with a dilute solution of sulphite lye and rammed into the space between a steel former and the chrome-magnesite bricks. Removal of the former left a hearth which was circular in horizontal cross-section and varied in diameter from 4 in. at the top to $2\frac{3}{4}$ in. at the base. As explained above, the shape of the hearth was found to be fairly critical, and this shape was used after a number of alternatives had been found unsatisfactory.

Thermocouple Sheath.

Electrically fused magnesia was finely ball-milled with 5% of titania and mixed with dilute acetone collodion to give a plastic mass. This was inserted into a small extrusion press fitted with a bridge die which enabled tubes of suitable cross-section to be prepared. As each length (5–6 in.) of tube was cut off, one end was sealed by pressing with a spatula dipped in acetone. The sheaths prepared in this manner were heated in an air-oven to drive off the acetone and then fired at 1700° C. in a gas-fired furnace. Considerable contraction occurred during firing and the sheaths were almost completely impervious.

Channels were cut in the walls of the freshly rammed hearth so that thermocouple sheaths could be inserted from opposite sides, as shown in Fig. 5, and the gaps rammed once more with the magnesia/sulphite-lye mix. The position of the thermocouple sheath was well below the slag–metal interface, but was such that molten metal would completely surround the tip. The completed hearth was allowed to dry overnight before use.

Materials Employed.

The commercially pure chemicals used in the preparation of the slags were :

(1) Precipitated chalk, which was calcined immediately before use.
(2) Precipitated silica, containing about 25% of moisture.
(3) Ferrous phosphate ($3FeO.P_2O_5.8H_2O$).
(4) Ferrous oxalate.
(5) Tribasic calcium phosphate.
(6) Manganous carbonate.
(7) Electrically fused alumina.

Preparation of Slags.

The necessary chemicals were weighed out in the required proportions and mixed in a small steel ball-mill for half an hour. Part of the mixture was then transferred to a fused-silica evaporating dish of $3\frac{1}{2}$ in. dia., and heated by an electric arc run between $\frac{1}{2}$-in. dia. carbon electrodes carrying a current of 20–35 amp. In the initial stages an indirect arc was used, but as soon as a pool of molten slag had been formed the electrodes were adjusted to give a direct arc through the slag. When the pool of molten slag was $1\frac{1}{2}$–2 in. long and about 1 in. in width, the arc was switched off and the slag allowed to solidify. After cooling, any unmelted chemicals adhering to the slag were brushed off, to leave a compact lump of about 50-g. weight, suitable for adding to the molten metal. A total of 250 g. of slag was used for each melt.

It will be noted that during preparation the slag came into contact only with its constituent chemicals, and there was no danger of contamination by other materials. The composition of the slag could be controlled within close limits, provided that the chalk was calcined before use; otherwise the evolution of carbon dioxide caused the powdered chemicals to be scattered, this effect being pronounced with the lighter constituents such as silica.

This method was also employed for synthesizing the standards required for the X-ray and petrographic examinations of the final slags, but in these cases water-quenching was used in an endeavour to prevent transformation in the solid state. The high temperature available in the arc enabled all the standards to be melted, and the resulting homogeneity, combined with the rapid quenching possible under these conditions,

FIG. 4.—General View of Apparatus.

FIG. 5.—Hearth before Melting.

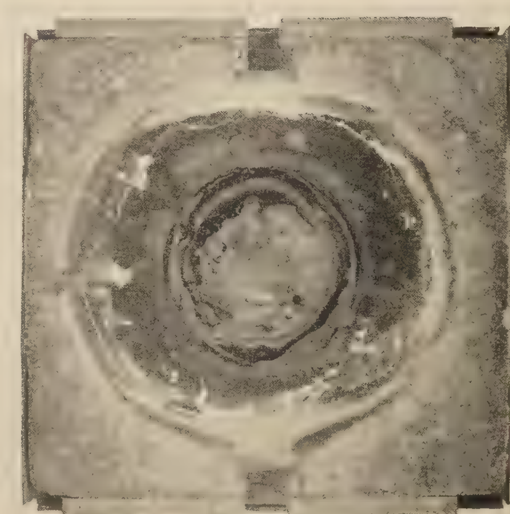


FIG. 6.—Hearth after Melting.

FIG. 7.—Slag and Metal Samplers.

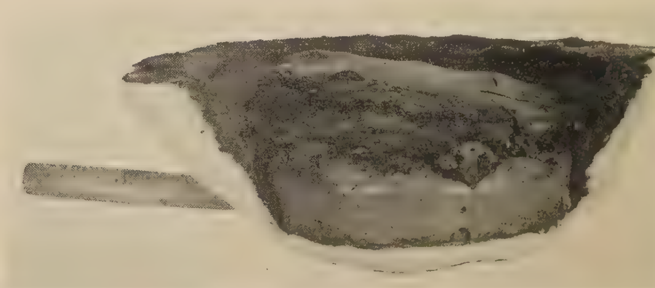


FIG. 8.—Hearth after Melting, showing slag and metal layers.

[*Balajiva, Quarrell, and Vajragupta.*

[*To face p.* 118 P.

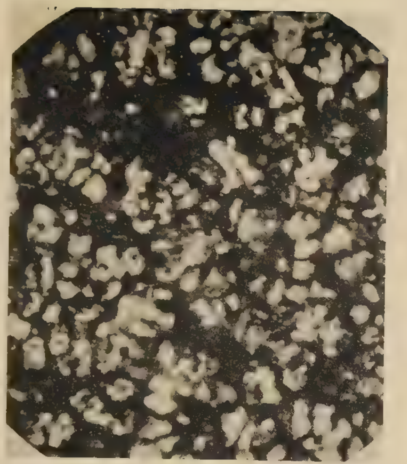


FIG. 9.—Slag containing CaO 47·6, SiO_2 12·2, FeO 15·1, P_2O_5 9·77, Fe_2O_3 6·7, MgO 6·2, MnO 1·3, Al_2O_3 1·0%. Transmitted light. × 130.

FIG. 10.—Slag containing CaO 39·6, SiO_2 10·8, FeO 17·2, P_2O_5 10·4, Fe_2O_3 5·5, MgO 7·0, MnO 5·8, Al_2O_3 4·1%. Transmitted light. × 130.

FIG. 11.—As Fig. 9, but seen through crossed nicols. × 130.

FIG. 12.—Large Crystals of MgO in process of dissolution into the oxide phase. Transmitted light. × 130.

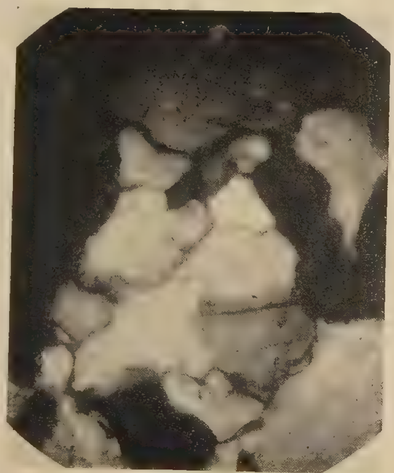


FIG. 13.—Standard *c*.

FIG. 14.—Standard *e* in powder form.

FIG. 15.—Standard *e* in thin section.

FIG. 16.—Standard *e* in thin section. Annealing has caused disintegration of the crystals.

FIGS. 13–16.—Slags Viewed through Crossed Nicols. × 130.

[*Balajiva, Quarrell, and Vajragupta.*

[*To face p.* 119 P.

makes this method of preparation more simple and, at the same time, more satisfactory than the usual repeated-sintering process.

Slag and Metal Samplers.

The slag sampler consisted of a copper block, 2 in. in dia. and 1 in. thick, with grooves near the lower edge and across a diameter of the lower face to prevent the slag falling off after solidification. A mild-steel rod of $\frac{1}{4}$ in. dia. and 18 in. long was screwed into the upper surface of the copper block, which was carefully degreased before taking a slag sample. The presence of grease on the copper prevented the slag from adhering to the sampler, but with a clean surface some 25 g. of slag were normally collected, having an average thickness of $\frac{1}{8}$ in.

The metal sampler employed in this work was similar in all important respects to that described by Taylor and Chipman. A $3\frac{1}{2}$-in. length of 1-in. dia. copper rod was drilled axially and then reamed with a standard No. 5 tapered pin reamer; this size gave a more solid sample than could be obtained with the No. 6 reamer used by Taylor and Chipman. A male $\frac{1}{2}$-in. gas thread was machined at the upper end of the copper rod, and the connection to the aspirator bulb was made with standard gas-fittings. It was found that the insertion of a plug of refractory brick into the tapered hole could be dispensed with, owing to the modified design of the connection between the copper mould and the steel tube. On the occasions when excess metal passed through the copper tube, it was still possible to unscrew the steel tubing and to saw off the projecting metal so that the sample could be ejected. In use, the outside of the copper rod was lightly greased with vaseline, the aspirator bulb was depressed, and the sampler pushed through the slag layer into the underlying metal. The bulb was then released and the sampler withdrawn almost immediately and quenched in cold water. The sample consisted of a fairly sound pencil, together with a thin mushroom-shaped layer which had chilled on to the lower end of the copper rod. The mushroom-shaped skull was cut off and only the pencil used for analytical purposes.

A photograph of the slag and metal samplers, together with typical samples, is reproduced in Fig. 7, in which the essential features are easily observed.

Melting Technique.

The metal charge of 600 g., in the form of pieces about $1 \times 1 \times \frac{1}{2}$ in., was packed into a hearth which had been allowed to dry in air but had not been fired. A platinum/platinum–13% rhodium thermocouple was inserted in one of the magnesia sheaths, whilst the other was held in reserve to be used in the event of failure of the first couple. After each melt at least 1 in. of couple was cut off and a new junction made to ensure freedom from contamination. The side walls of the furnace were then placed in position on top of a layer of asbestos packing, and the electrode holders were positioned so that all necessary adjustments could be made during the course of the melt. The roof and graphite lid of the furnace were placed in position with asbestos packing between successive layers.

The supply of cylinder nitrogen was switched on and the arc started between the electrodes at an angle of about 20°. During the melting-down period the arc was indirect and the current was gradually raised from 100 to 150 amp. in about 20–30 min. At the end of this time the metal was beginning to melt and slag was added in lumps of approximately 50 g. at a time. At the same time the angle made by the electrodes with the horizontal was increased in stages to 30–40°, in order to obtain a direct arc with a distance of about 1 in. between the tips of the electrodes. The arc current was maintained at 150 amp. during this period and until the required temperature was reached, when control with the variable choke was commenced. It was found that when the bath was completely molten the electrodes had to be separated to $1\frac{1}{2}$ in. to prevent arcing between them. The direct arc, using well-separated electrodes, gave more uniform heating, but care had to be taken that the electrodes were not too near the hearth refractory, nor touching the slag.

In the first few melts the temperature was kept constant for 20 min., but with increasing experience it became desirable and possible to hold the temperature within close limits for a longer period, and 40 min. was taken as standard. The accuracy of temperature control depended to a large extent upon the nature of the slag. With a fairly viscous slag a record was obtained showing fluctuations of $\pm 25°$ C.; very few records were as bad as this, the majority showing a variation of less than $\pm 10°$ C. Under the most favourable conditions, the temperature could be maintained constant to within $\pm 5°$ C.

On many occasions the reliability of temperature measurement was checked by placing a new thermocouple in the reserve sheath and transferring the amplifier to this circuit. In all cases, except where contamination of the first thermocouple was obvious, there was no resulting discontinuity on the temperature record.

When the bath had been held at a constant temperature for the required length of time, the arc was switched off, the electrodes and thermocouple were rapidly withdrawn and the slag sampler was pressed down into the slag through the hole exposed by removing the graphite furnace lid. As soon as the slag sample had been obtained and

quenched in water, the metal was sampled twice in quick succession, using two samplers. The time elapsing between the end of the melt and the completion of the sampling operation was a matter of seconds, and the total time taken by a complete experiment varied from 1 to $1\frac{1}{2}$ hr.

After the slag and metal samples had been taken, the furnace and its contents were allowed to cool, with the graphite plug removed. It was found that the slag in the furnace solidified almost immediately after sampling, and that black heat was reached in 20–30 min. The appearance of a hearth after melting is illustrated in Fig. 6, whilst Fig. 8 shows the appearance of the charge after removal from the brickwork. The slag and metal layers are clearly visible, and it will be seen that the thermocouple sheath is suitably placed with respect to the metal charge. Slag attack of the magnesia hearth is small, and this is confirmed by the analyses of the final slags (*see* Table I.).

Analytical Procedure.

The two metal pencils were carefully machined to give a total of 10–15 g. of fine turnings. Standard methods of analysis were used throughout, the gravimetric lead molybdate method being employed for the determination of phosphorus.

After the slag sample had been dried by heating in an oven at 110° C., it was crushed with a percussion mortar to pass a 30-mesh sieve. Any particles of iron present were removed with a magnet, and a suitable portion of slag weighing about 5 g. was obtained from the crushed product by taking samples at nine points. This was further crushed to pass a 90-mesh sieve, and finally ground in an agate mortar for analysis.

All slags obtained in the experimental work were analysed for CaO, SiO_2, P_2O_5, FeO, Fe_2O_3, Al_2O_3, MnO, and MgO. It was found that the slags contained only traces of metallic iron, insufficient, in fact, to have any significant effect upon the determination of ferrous and ferric iron, and the regular determination of metallic iron was therefore discontinued. The presence of so little metallic iron in the slags showed that the reaction $3FeO \longrightarrow Fe_2O_3 + Fe$ had been almost completely suppressed during the sampling operation and indicated the efficiency of the precautions taken to retain in the sample the slag conditions at high temperatures.

Determination of Ferrous and Ferric Iron.—The total iron content of the slag was determined by the usual method of reduction with stannous chloride and titration with standard potassium dichromate solution, using 0·2% of barium diphenylamine sulphonate as an internal indicator.

Ferrous iron was determined by weighing a fresh 0·5-g. sample of slag, together with about 1·0 g. of sodium carbonate, into a 500-ml. conical flask fitted with a Bunsen valve. Some 15 ml. of distilled water and 20 ml. of concentrated hydrochloric acid were then added and solution was effected by gentle boiling for about 10 min., the evolution of carbon dioxide maintaining a neutral atmosphere and preventing the oxidation of the ferrous iron. When solution was complete the Bunsen valve was removed and the contents of the flask quickly cooled in running water. About 15 ml. of sulphuric/phosphoric-acid mixture were then added, and after standing for 1 min. the solution was titrated with standard potassium dichromate solution, using the diphenylamine indicator as before.

Ferric iron was taken as the difference between the total and ferrous iron results.

Determination of P_2O_5.—A separate sample was used in this case, and the phosphorus was estimated gravimetrically as $Mg_2P_2O_7$. This method was found to be more satisfactory than the lead molybdate method, owing to the presence of large amounts of P_2O_5 in all the slags examined.

Determination of MnO.—The determination of MnO was carried out on a separate sample, using the standard bismuthate method.

Determination of SiO_2, Al_2O_3, CaO, and MgO.—These constituents were determined on the same sample by the method of group separation. The silica estimation calls for little comment except that it was found that accurate results could be obtained only if the silica was filtered off between the first and second evaporations and bakings of the filtrate.

Considerable difficulty was experienced in the separation of iron, alumina, and P_2O_5, especially with slags containing large percentages of P_2O_5, because under these conditions lime is likely to precipitate as phosphate unless special precautions are taken. This difficulty was overcome by adding a suitable proportion of $FeCl_3$ to those slags which were low in iron and by using the double basic-acetate method of separation. The precipitate was used for the determination of alumina and the filtrates for lime and magnesia.

To prevent its interference with the precipitation of aluminium phosphate, iron was previously removed by caustic soda separation. Other more accurate methods are available for the determination of alumina in slags, but this method was adopted because of its simplicity, and the accuracy of the results so far obtained seems to be adequate for the purpose.

Lime was determined gravimetrically by precipitation as calcium oxalate followed by ignition to CaO, whilst magnesia was estimated as magnesium pyrophosphate in the usual manner.

Reliability of the Analytical Results.—The determinations of phosphorus in the metal and of P_2O_5, CaO, and SiO_2 in the slag were carried out independently by two workers, and the results

were not utilized unless the agreement was good. The sums of the constituents determined fell between 98 and 102% in all analyses, whilst most of them were within the limits 99·5–100·5%, and this, taken with the fact that the results responded satisfactorily to theoretical treatment, may be taken as an indication that the analytical methods and technique employed were sound.

Application of the Technique to the Phosphorus Reaction in the Basic Steelmaking Process.

The phosphorus reaction in the basic steelmaking process is so complex, and the difficulties associated with the investigation of reactions at steelmaking temperatures so great, that our understanding of this reaction is still far from complete, in spite of the amount of work already carried out on the problem. When a satisfactory new technique for melting slag and metal together under strict conditions of slag and temperature control had been devised, a new attack upon the problem became possible, and an account will now be given of the work carried out with a view to elucidating the nature of the phosphorus reaction.

Review of Previous Work on the Phosphorus Reaction.

Investigations of the pure system consisting of phosphorus–iron and a slag of iron phosphate and iron oxide have been conducted by various workers, including Herty [3] Samson-Himmelstjerna,[4] Krings and Schackmann,[5] and Maurer and Bischoff,[6] but these authorities do not agree in their conclusions as to the formulation of the equilibrium constant. It would seem that dephosphorization is primarily a straightforward oxidation of the phosphorus in the iron by ferrous oxide according to the equation :

$$2P + 5FeO \rightleftharpoons P_2O_5 + 5Fe, \quad . \quad . \quad (1)$$

but matters are complicated by the fact that phosphorus pentoxide is not stable but vaporizes at high temperatures. Free phosphorus pentoxide cannot therefore exist in the slag, but must be combined in some way, most probably as iron phosphate in the pure system. In addition, relatively little is known about the state of phosphorus in molten iron, and it is not surprising that different workers have developed different formulæ for the evaluation of the phosphorus equilibrium constant. Thus, Krings and Schackmann have developed their formula from equation (1), but with substitution of [P] for $[P]^2$, to give :

$$K = \frac{(P_2O_5)[Fe]^5}{[P](FeO)^5}.$$

They explain their action on the grounds of the absence of any real knowledge of the state of phosphorus in molten iron, and point out that raising the power of [P] would magnify any analytical errors. Maurer and Bischoff, on the other hand, could not put forward any definite equilibrium constant from their experimental results, but were able to give a practical description of the equilibrium conditions by introducing the distribution factor $(P_2O_5)/[P]$.

With the exception of Maurer and Bischoff, the workers mentioned above agree that the P–Fe–FeO–P_2O_5 system exhibits non-ideal behaviour at low concentrations of P_2O_5. As a result of their work on the FeO–CaO–P_2O_5 system, Oelsen and Maetz [7] came to the conclusion that there was a lens-shaped region of immiscibility extending from the ferrous oxide corner, across the FeO–CaO–P_2O_5 ternary diagram to the point corresponding to calcium orthophosphate. On the basis of this conclusion they suggest that the non-ideal behaviour of the pure system containing less than 25% of P_2O_5 could be explained in terms of a tendency for the ferrous oxide and iron phosphate to separate into two immiscible layers. Their work also led them to the conclusion that silica exerted a considerable influence in closing the immiscibility gap, and that in the presence of sufficient silica the slag would probably be entirely miscible. In his work on phosphate slags, Trömel [8] has confirmed that this is actually the case and so has given support to the general statement made by Lorenz [9] that non-ideal solutions may be made ideal by the addition of other constituents. There is some reason for believing, therefore, that in complex slags the ideal law of mass action will be more closely followed.

Most of the work using complex slags has been carried out in the steelworks; so far it has not been found possible to establish the phosphorus reaction on a definite quantitative basis, and the methods adopted in controlling the dephosphorization of the steel-bath are based on works' experience. Such methods may be very useful in practice, but they are lacking in scientific precision and incapable of general application. Many workers have attempted to find the general principles underlying the dephosphorization process and to give a quantitative treatment. Thus, Whiteley,[10] using his works' data, obtained a linear relationship between the distribution factor $(P_2O_5)/[P]$ and his arbitrary "basicity index," *i.e.*, the best straight line passing through the point corresponding to no dephosphorization at basicity index 2. Similarly, McCance [11] obtained a linear relationship when he plotted

$$\frac{(P_2O_5)}{[P]} \cdot \frac{1}{(P_2O_5) + (FeO)}$$

against total lime, and by extrapolation showed that no dephosphorization should occur if the slag contained less than 32% of total lime.

An entirely different method of approach has

been used by Schenck and Riess,[12] who assumed that every slag constituent is present both in the free state and in combination. By making further assumptions, not entirely based on experimental evidence, they were able to calculate the so-called "free concentration" of each constituent. Even using these free concentrations they were unable to formulate the phosphorus equilibrium constant quantitatively, but found it necessary to substitute [P] for $[P]^2$ and to introduce an empirical correction factor the value of which depended upon the P_2O_5 concentration in the slag. On the assumption of calcium triphosphate formation, they gave the equation :

$$\text{Log } K_P = \log \frac{[P](FeO)^5(CaO)^3}{(\Sigma P_2O_5)} + 0{\cdot}045(\Sigma P_2O_5) \quad . \ (2)$$

and on the basis of tetraphosphate :

$$\text{Log } K_P = \log \frac{[P](FeO)^5(CaO)^4}{(\Sigma P_2O_5)} + 0{\cdot}060(\Sigma P_2O_5) \quad . \ (3)$$

In view of the many assumptions made in the derivation of these equations and the empirical nature of the final result, it is doubtful whether much importance should be attached to them, although Zea [13] claims that better agreement is obtained between calculated and actual values of phosphorus contents if the equations of Schenck and Riess are used rather than, for example, those of Whiteley.

In spite of the absence of quantitative agreement between the different workers, it is possible to give a qualitative outline of the dephosphorization process, which would be generally acceptable, as follows :

(*a*) Ferrous oxide is necessary for the oxidation of phosphorus in the metal phase.

(*b*) Lime is necessary for dephosphorization.

(*c*) As the oxidation of phosphorus is an exothermic reaction, dephosphorization decreases with increasing temperature.

(*d*) The proportion of phosphorus in the metal after dephosphorization is dependent on the P_2O_5 content of the slag, the smaller this value the better being the dephosphorization.

Whilst it is agreed that slag composition plays a decisive rôle in dephosphorization, the effect of constituents other than those mentioned above is still not fully understood. The possibilities are that the constituent (*a*) is an active participant in the phosphorus reaction, and (*b*) affects dephosphorization indirectly by mere dilution or by combining with one of the active constituents or with a constituent, such as silica, which usually takes up some of the directly active constituents.

Range of Slag and Metal Compositions Employed in the Present Work.

It was considered desirable that the results of this work should be, as far as possible, directly applicable to the steelmaking process and at the same time should cover a wider range of slag compositions than is normally employed in practice. Thus the fluxes MnO, P_2O_5, and Al_2O_3 were added to all slags both because they are always present in industrial slags and because they lower the melting point and viscosity, thus enabling the investigation to be carried out over a wider range of analyses and at lower temperatures than would otherwise be possible. The fluxes were held within fairly close limits, except where the effect of a given constituent was being examined, and the range of slag compositions employed was as follows :

CaO .	30–57%.
SiO_2 .	10–25%.
FeO .	4–32%.
Fe_2O_3 .	1·0–7·5% (usually 4–5%).
MnO .	1–1·5%, with special series containing 5–6% and 11%, respectively.
P_2O_5 .	8–12%, with special series containing 5–6%.
Al_2O_3 .	2–5%, with special series containing 8%.
MgO .	3·0–12·3%.

A total weight of 250 g. of slag was used for each melt, and it was found convenient to keep the lime/silica ratio constant for a given series of melts, and to vary the FeO content of the slag. As the percentage of FeO was increased, the lime and the silica contents were both diminished, so that a wide range of compositions was covered. Magnesia was not deliberately added to the slag, but was dissolved from the hearth. The more basic the slag and the higher the MnO content, the less was the MgO pick-up. Similarly, Fe_2O_3 was not added but was formed during melting as a result of the oxidation of part of the FeO. As a general rule it was found that the Fe_2O_3/FeO ratio increased with the basicity of the slag, which is in agreement with other work.

In view of the difficulties which had been encountered when high-carbon charges were employed and also to simplify the problem, the metal used throughout this work was relatively pure, except for phosphorus content. A master 2% phosphorus alloy was prepared by dissolving iron phosphide in molten ingot iron in a high-frequency furnace and casting into 1-in. dia. ingots. Dilution of 125 g. of this phosphorus iron with 475 g. of ingot iron gave a charge with an initial phosphorus content of approximately 0·4%. After a number of melts had been carried out, recrystallized-alumina thermocouple insulators became available, and it was found possible to carry out successful melts with carbon contents of the order of 0·6%. Although all the experiments with which this paper is concerned were carried out with low carbon in the steel, there now appears to be no reason why the work should not be extended to high-carbon material.

Table I.—*Slag and Metal Analyses Obtained in the Study of Dephosphorization at* 1585 ± 10° *C.*

Melt No.	Time at 1585 ± 10° C.	P in Metal, wt.-%.	Slag Analysis, wt.-%.								$(CaO)/(SiO_2)$, wt.-%.	$(P_2O_5)/[P]$, wt.-%.	P in Metal, at.-%.	Slag Analysis, mol.-%.							
			P_2O_5.	CaO.	SiO_2.	FeO.	Fe_2O_3.	Al_2O_3.	MnO.	MgO.				P_2O_5.	CaO.	SiO_2.	FeO.	Fe_2O_3.	Al_2O_3.	MnO.	MgO.
*A*5	20	0·094	8·29	34·4	12·3	24·5	6·0	3·4	1·4	8·7	2·8	88	0·167	3·84	40·3	13·5	22·4	2·5	2·2	1·3	14·2
*A*6	25	0·036	9·69	43·0	15·5	13·2	5·2	3·7	1·4	8·2	2·8	269	0·069	4·35	48·9	16·5	11·7	2·1	2·3	1·2	13·0
*A*7	20	0·063	7·14	34·6	12·0	25·2	7·4	3·2	1·2	8·6	2·9	114	0·111	3·30	40·4	13·1	23·0	3·0	2·1	1·2	14·0
*A*8	20	0·047	7·27	38·0	13·4	17·8	4·4	3·6	1·4	13·0	2·9	155	0·083	3·15	41·9	13·8	15·4	1·7	2·2	1·2	19·9
*A*10	20	0·105	9·83	47·6	17·8	9·6	3·0	3·4	1·5	6·9	2·7	94	0·187	4·34	53·4	18·6	8·4	1·2	2·1	1·3	10·7
*A*11	20	0·134	10·61	50·0	17·7	8·0	2·1	3·4	0·9	6·8	2·8	79	0·232	4·67	55·8	18·5	6·9	0·8	2·1	0·8	10·5
*A*12	20	0·143	10·33	50·0	17·4	6·8	2·1	3·7	1·4	6·7	2·9	72	0·250	4·59	56·2	18·4	6·0	0·9	2·3	1·2	10·5
*A*13	8	0·036	9·57	45·6	15·0	13·8	4·2	3·7	1·3	6·0	3·0	266	0·064	4·34	52·4	16·1	12·4	1·7	2·3	1·2	9·7
*A*14	20	0·089	8·49	33·7	10·6	28·4	5·0	4·1	1·4	8·0	3·2	95	0·161	3·92	39·7	11·6	26·0	2·1	2·6	1·3	13·0
*A*15	20	0·081	6·13	30·4	9·8	31·6	6·1	5·3	1·2	9·7	3·1	76	0·146	2·82	35·4	10·6	28·6	2·5	3·4	1·1	15·7
*A*16	20	0·091	9·17	46·6	14·9	11·6	4·3	4·7	1·2	7·3	3·1	101	0·164	4·09	52·7	15·7	10·2	1·7	2·9	1·1	11·5
*A*17	20	0·067	10·15	49·5	16·2	10·2	0·9	3·4	1·1	7·8	3·1	152	0·121	4·43	54·8	16·8	8·8	0·3	2·1	0·9	12·0
*B*1	25	0·132	9·00	48·5	18·5	7·6	2·6	3·6	1·2	8·2	2·6	68	0·238	3·92	53·7	19·1	6·6	1·0	2·2	1·0	12·6
*B*2	20	0·056	9·67	46·5	17·3	9·9	2·7	5·5	1·2	8·0	2·7	173	0·101	4·22	51·6	17·9	8·6	1·1	3·4	1·0	12·4
*B*3	20	0·127	10·45	50·3	17·8	7·3	1·7	4·0	1·3	7·8	2·8	82	0·229	4·52	55·2	18·2	6·3	0·7	2·4	1·1	11·8
*C*1	20	0·080	9·60	34·8	14·7	22·7	4·2	3·0	1·6	9·8	2·4	120	0·154	4·27	39·6	15·6	20·2	1·7	1·9	1·5	15·5
*C*2	20	0·069	8·80	35·2	14·8	21·5	3·9	4·6	1·6	10·4	2·4	128	0·121	3·92	39·7	15·4	19·0	1·6	2·8	1·4	16·3
*C*3	20	0·076	9·27	39·2	16·8	16·5	4·3	5·2	1·6	9·4	2·5	122	0·126	4·01	44·0	16·6	14·5	1·7	3·2	1·4	14·7
*C*4	20	0·087	9·63	44·6	18·6	11·1	1·9	3·0	1·4	9·2	2·5	111	0·156	4·18	49·4	19·0	9·6	0·7	1·8	1·2	14·2
*C*5	20	0·141	9·38	46·6	20·1	6·8	2·5	3·8	1·3	10·1	2·3	67	0·254	4·01	50·4	20·3	5·7	0·9	2·3	1·1	15·2
*C*6	20	0·139	9·06	47·0	20·4	7·7	1·8	4·0	1·3	8·8	2·3	65	0·250	3·90	51·3	20·8	6·5	0·7	2·4	1·1	13·3
*C*7	20	0·073	8·73	43·6	17·5	12·6	3·1	4·1	1·3	8·8	2·5	120	0·132	3·84	48·6	18·3	11·0	1·2	2·5	1·2	13·6
*C*8	20	0·105	9·28	47·8	19·7	8·8	1·3	4·0	1·4	7·8	2·4	88	0·189	4·01	52·4	20·2	7·5	0·5	2·4	1·2	11·9
*C*9	20	0·208	8·82	49·8	20·5	5·9	1·4	4·2	1·1	8·6	2·4	42	0·377	3·76	53·8	20·7	5·0	0·5	2·5	0·9	12·9
*C*10	20	0·098	8·80	33·6	14·0	21·2	2·8	4·3	1·6	14·9	2·4	90	0·177	3·78	36·6	14·2	18·0	1·0	2·6	1·4	22·6
*C*11	20	0·074	9·10	32·4	13·4	23·5	4·2	4·3	1·7	12·3	2·4	123	0·133	4·03	36·4	14·0	20·7	1·6	2·6	1·5	19·2
*D*1	20	0·040	10·10	40·4	11·5	21·2	5·2	4·2	1·6	7·3	3·5	252	0·072	4·58	46·6	11·9	19·0	2·1	2·6	1·5	11·7
*D*2	28	0·039	8·80	37·6	11·5	21·6	4·1	4·6	1·6	11·6	3·3	226	0·070	3·87	42·0	11·6	18·8	1·6	2·8	1·4	18·0
*D*3	20	0·037	10·20	46·0	13·6	15·9	5·1	3·4	1·4	6·5	3·4	276	0·067	4·53	51·7	14·3	14·0	2·0	2·1	1·3	10·1
*D*4	20	0·037	9·77	40·9	11·4	22·1	5·7	4·4	1·6	8·2	3·6	264	0·067	4·31	45·7	11·9	19·3	2·2	2·7	1·4	12·8
*D*5	20	0·028	9·06	46·7	12·6	16·6	5·8	3·2	1·5	6·3	3·7	324	0·050	4·05	52·8	13·3	14·6	2·3	2·0	1·3	9·9
*D*6	20	0·030	9·77	51·6	13·9	13·6	4·7	2·8	1·5	5·8	3·7	326	0·054	4·22	56·4	14·2	11·6	1·8	1·7	1·3	8·8
*D*7	20	0·116	10·65	58·1	15·5	6·6	2·2	2·8	1·3	7·1	3·7	92	0·210	4·41	61·0	15·2	5·4	0·8	1·6	1·1	10·4
*D*8	35	0·110	10·15	56·1	15·8	7·9	2·3	3·0	1·2	5·8	3·5	92	0·198	4·36	60·6	16·0	6·7	0·9	1·8	1·0	8·7
*D*9	20	0·086	13·30	48·9	14·4	9·0	3·3	4·1	1·6	6·7	3·4	155	0·155	5·93	55·3	15·2	7·9	1·3	2·5	1·4	10·5
*D*11	20	0·189	11·00	54·9	17·5	4·5	1·6	3·7	1·1	7·1	3·2	58	0·341	4·70	59·5	17·7	3·8	0·6	2·2	0·9	10·7
*D*12	20	0·049	10·30	51·4	15·7	9·2	3·6	4·0	1·4	5·7	3·3	210	0·088	4·53	57·4	16·4	8·0	1·4	2·5	1·3	8·8
*D*13	20	0·052	10·90	34·3	9·6	27·6	6·6	3·2	1·5	7·7	3·6	210	0·094	5·05	40·3	10·5	25·3	2·7	2·1	1·4	12·6
*E*1	20	0·037	10·66	41·3	10·7	19·1	5·5	3·4	1·6	6·5	3·9	288	0·067	4·97	49·0	11·8	17·6	2·3	2·2	1·5	10·7
*E*2	20	0·029	10·22	44·0	11·6	17·6	6·4	3·7	1·5	6·3	3·8	352	0·052	4·65	50·7	12·5	15·8	2·6	2·4	1·3	10·1
*E*3	20	0·056	12·20	37·2	8·8	23·6	6·9	3·9	1·6	7·0	4·2	218	0·101	5·72	44·2	9·8	21·9	2·9	2·5	1·5	11·6
*E*4	20	0·027	12·60	45·5	11·6	15·8	6·4	1·8	1·3	5·4	3·9	465	0·049	5·82	53·3	12·7	14·4	2·6	1·2	1·2	8·8
*E*5	20	0·035	12·70	49·8	12·2	11·6	4·7	3·3	1·3	6·1	4·1	363	0·063	5·68	56·5	12·9	10·3	1·9	2·1	1·2	9·6
*E*6	20	0·040	11·70	50·6	12·4	9·5	3·9	3·6	1·3	7·7	4·1	293	0·073	5·17	56·7	13·0	8·3	1·5	2·2	1·2	12·0
*E*7	20	0·051	12·30	41·4	10·0	19·3	6·6	1·7	1·6	6·9	4·1	241	0·092	5·73	48·9	11·0	17·8	2·7	1·1	1·5	11·3
*P*1	40	0·022	5·63	35·7	10·8	28·1	7·6	2·6	5·6	4·3	3·3	256	0·040	2·63	42·3	11·9	25·9	3·2	1·7	5·2	7·1
*P*2	40	0·018	5·41	42·0	12·7	22·2	8·3	2·6	5·2	2·3	3·3	300	0·032	2·51	49·4	14·0	20·4	3·4	1·7	4·8	3·8
*P*3	40	0·020	6·00	46·2	13·8	14·7	6·7	3·1	6·1	4·3	3·3	300	0·036	2·70	52·7	14·7	13·1	2·7	1·9	5·5	6·8
*P*4	40	0·016	5·41	43·6	12·6	17·4	7·1	2·9	5·8	5·4	3·5	338	0·029	2·45	50·0	13·5	15·6	2·8	1·8	5·3	8·6
*P*5	40	0·019	6·11	43·5	13·5	18·2	7·1	2·7	5·6	3·8	3·2	320	0·034	2·79	50·4	14·6	16·5	2·9	1·8	5·1	6·1
*P*6	40	0·018	5·24	42·3	12·3	18·5	7·7	2·6	5·8	4·6	3·4	292	0·032	2·42	49·6	13·5	16·9	3·2	1·7	5·4	7·5
*P*7	40	0·016	5·15	42·1	12·3	20·1	7·7	2·4	5·3	4·5	3·4	320	0·029	2·37	49·1	13·4	18·3	3·1	1·6	4·9	7·3
*P*8	40	0·018	5·22	46·9	13·0	14·6	6·8	3·0	6·0	4·1	3·6	290	0·032	2·37	53·8	14·0	13·1	2·8	1·9	5·5	6·6
*P*9	40	0·014	4·60	40·6	11·7	21·6	9·2	2·2	5·1	4·7	3·5	329	0·025	2·13	47·7	12·8	19·8	3·8	1·4	4·7	7·7
*Al*1	40	0·036	9·10	42·4	11·0	18·4	6·3	8·0	1·5	6·0	3·9	253	0·065	4·14	48·8	11·8	16·5	2·6	5·1	1·4	9·6
*Al*2	40	0·031	9·02	43·8	11·0	17·3	5·5	7·2	1·3	6·2	4·0	290	0·056	4·10	50·6	11·9	15·6	2·2	4·6	1·2	9·9
*Al*3	30	0·044	10·50	48·6	12·3	12·3	4·7	7·2	1·3	3·4	4·0	239	0·079	4·87	57·1	13·5	11·3	1·9	4·6	1·2	5·6
*Al*4	30	0·040	10·10	48·4	12·5	13·3	6·0	6·9	1·2	2·6	3·9	253	0·072	4·69	57·0	13·7	12·2	2·5	4·5	1·1	4·3
*Al*5	30	0·035	9·65	46·0	11·8	15·3	5·4	7·2	1·4	5·1	3·9	276	0·063	4·39	53·0	12·7	13·7	2·2	4·6	1·3	8·2
*Al*6	30	0·041	9·25	42·3	11·5	18·4	5·4	6·8	1·5	5·6	3·7	226	0·074	4·26	49·4	12·6	16·7	2·2	4·4	1·4	9·1
*Al*7	30	0·040	9·32	44·5	11·8	15·1	5·1	7·5	1·8	6·1	3·8	233	0·072	4·23	51·3	12·7	13·6	2·1	4·8	1·6	9·8
*Al*8	30	0·047	10·45	47·8	13·2	11·8	4·5	7·2	1·8	3·3	3·6	222	0·085	4·86	56·3	14·5	10·8	1·9	4·7	1·7	5·4
*Al*9	30	0·058	9·35	48·7	13·4	10·5	3·8	7·4	1·7	3·9	3·6	162	0·105	4·33	57·2	14·7	9·6	1·6	4·8	1·6	6·4
*Al*10	30	0·046	10·00	47·8	13·2	12·6	5·2	7·3	1·8	2·9	3·6	218	0·083	4·63	56·1	14·5	11·5	2·1	4·7	1·7	4·7
*Mn*4	20	0·047	10·60	37·6	10·1	20·6	6·0	4·6	6·0	6·1	3·7	226	0·085	4·94	44·2	11·1	18·9	2·5	3·0	5·6	10·0
*Mn*6	20	0·075	12·30	47·4	12·5	8·9	3·2	4·4	6·0	5·9	3·8	164	0·136	5·58	54·4	13·3	8·0	1·3	2·8	5·5	9·4
*Mn*7	20	0·091	13·10	48·3	13·2	9·3	3·1	4·2	5·9	5·6	3·7	144	0·164	5·81	54·3	13·8	8·2	1·2	2·6	5·2	8·7
*Mn*10	20	0·042	10·70	43·6	11·8	15·7	6·0	3·5	6·2	3·9	3·7	255	0·076	4·93	50·9	12·9	14·3	2·5	2·2	5·7	6·3
*Mn*11	20	0·036	8·76	40·5	12·5	21·4	6·8	3·3	5·0	4·2	3·2	244	0·065	4·00	47·0	13·5	19·4	2·8	2·1	4·5	6·8
*Mn*12	20	0·043	10·80	40·0	11·0	19·3	5·4	2·6	5·7	5·6	3·6	255	0·077	5·00	47·1	12·0	17·0	2·2	1·7	5·3	9·1
*Mn*13	20	0·049	12·30	44·0	11·8	12·4	6·1	3·4	6·0	4·1	3·7	251	0·088	5·78	52·4	13·1	11·5	2·6	2·2	5·6	6·8
*MnX*1	30	0·049	10·50	35·1	9·3	24·4	6·3	2·8	6·7	5·3	3·8	214	0·088	4·97	42·1	10·4	22·8	2·6	1·8	6·4	8·9
*MnX*2	40	0·039	10·90	40·1	11·1	19·1	6·3	2·7	6·6	4·4	3·6	280	0·070	5·09	47·4	12·3	17·6	2·6	1·8	6·2	7·2
*MnX*3	40	0·050	12·30	42·7	11·7	14·2	5·6	2·8	6·3	4·3	3·7	246	0·090	5·78	50·8	13·0	13·2	2·3	1·8	5·9	7·1
*MnX*4	40	0·044	10·50	36·4	10·0	22·6	7·2	3·2	6·4	4·8	3·6	239	0·079	4·97	43·7	11·2	21·2	3·0	2·1	6·0	8·0
*MnX*5	40	0·047	12·50	41·4	11·5	15·6	5·6	3·0	6·2	5·1	3·6	266	0·085	5·81	48·9	12·7	14·3	2·3	1·9	5·7	8·4
*MnX*7	40	0·065	13·70	46·2	12·8	10·4	4·4	3·2	6·4	3·7	3·6	211	0·117	6·34	54·2	14·1	9·5	1·8	2·0	5·9	6·0
*MnX*8	40	0·043	12·20	45·0	12·5	13·3	5·1	3·4	6·3	3·1	3·6	284	0·078	5·68	53·2	13·8	12·2	2·1	2·2	5·9	5·1
*MnY*1	40	0·077	11·31	32·6	8·8	21·9	6·1	3·4	11·8	5·1	3·7	148	0·139	5·38	39·4	9·9	20·6	2·6	2·2	11·2	8·6
*MnY*2	40	0·054	9·53	32·8	8·8	23·7	6·4	3·3	11·3	5·3	3·7	177	0·098	4·51	39·4	9·9	22·2	2·7	2·1	10·7	8·9
*MnY*3	40	0·055	11·20	36·8	10·0	18·1	5·6	3·0	11·2	5·1	3·7	206	0·100	5·25	43·8	11·1	16·8	2·3	1·9	10·5	8·4
*MnY*4	40	0·058	10·95	37·5	9·9	17·0	6·1	3·2	11·2	5·2	3·8	189	0·105	5·13	44·5	11·0	15·8	2·5	2·1	10·5	8·6
*MnY*5	40	0·049	11·10	40·5	11·1	13·9	5·3	3·1	11·5	3·8	3·7	228	0·089	5·21	48·3	12·3	12·9	2·2	2·0	10·8	6·3
*MnY*6	40	0·041	8·50	34·8	9·5	22·9	6·4	3·0	11·1	4·1	3·7	207	0·074	4·03	41·9	10·6	21·4	2·7	2·0	10·6	6·9
*MnY*7	40	0·043	8·09	33·8	8·8	23·7	7·0	2·5	10·5	5·7	3·8	188	0·078	3·81	40·3	9·8	22·0	2·9	1·7	9·9	9·5
*MnY*10	40	0·046	9·24	36·1	9·4	21·5	6·9	2·8	10·6	4·4	3·8	201	0·083	4·36	42·9	10·5	20·1	2·9	1·9	10·1	7·3
*MnY*11	40	0·053	9·92	39·8	10·4	16·6	5·6	3·4	11·3	3·6	3·8	188	0·096	4·66	47·2	11·6	15·4	2·3	2·2	10·7	5·9
*MnY*12	40	0·046	10·50	41·3	11·1	14·2	5·2	3·2	11·7	3·9	3·7	228	0·083	4·87	48·3	12·2	13·0	2·2	2·0	10·9	6·4

Experimental Results.

All the experimental work to be described was carried out at 1585 ± 10° C. and the analytical results are given in detail in Table I. For the first four series of melts *A*, *C*, *D*, and *E*, slags containing the normal amounts of fluxes, as indicated, and with lime/silica ratios of 2·8, 2·4, 3·5, and 4·0 respectively, were employed. The FeO content was varied over a wide range for each series and the values of the distribution factor $(P_2O_5)/[P]$ were calculated and are plotted against the FeO content in Fig. 17. It will be

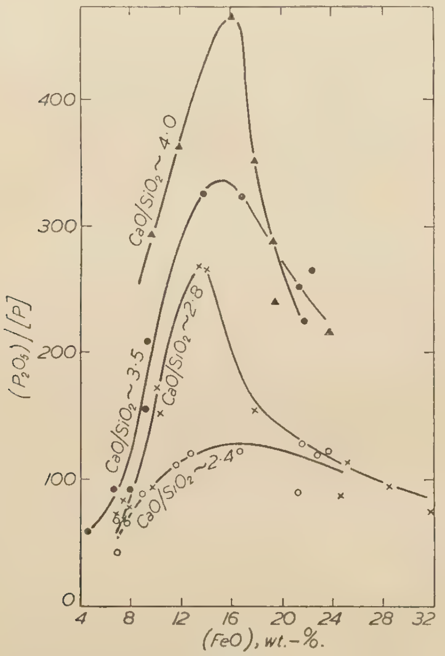


FIG. 17.—Relationship between (FeO) and $(P_2O_5)/[P]$ Ratio.

seen that for each lime/silica ratio there is an optimum FeO content at which the value of the distribution factor $(P_2O_5)/[P]$ is a maximum, and that the maximum value of this factor increases with the basicity of the slag. With a lime/silica ratio of 2·4, the maximum is broad, and over the range 12–22% by weight of FeO the value of the distribution factor is 120–130. The peak becomes very pronounced when the lime/silica ratio is increased to 2·8, and reaches a maximum value of 270 at 13–14% by weight of FeO. As the lime/silica ratio is increased still further, the maximum distribution factor is also increased, so that with $CaO/SiO_2 = 3·5$ the maximum value of 340 occurs at 15% of FeO, and with $CaO/SiO_2 = 4·0$ the corresponding value is 460 at 16% of FeO.

At first sight, the form of these curves may appear to conflict with practical experience, but it can be explained on the assumption that both FeO and CaO are essential for dephosphorization. Thus, considering the curve for a lime/silica ratio of 4·0, for FeO contents below 16% there is ample lime available and the value of the distribution factor is governed mainly by the amount of FeO present; this is in agreement with industrial experience. The peak, which will be considered in more detail later, corresponds to the point at which the optimum combined effect of CaO and FeO is operative. Any increase in FeO carried out in a slag of fixed lime/silica ratio must result in a decrease in the lime content, and, in the example under discussion, increasing the FeO beyond 16% causes a deficiency of lime which is responsible for the sudden drop in the distribution factor observed in this range.

Curves of similar shape, but with rather greater scatter of the experimental points, are obtained if the total iron content expressed as FeO is used instead of the analytically determined ferrous oxide content of the quenched slag. When the results are plotted in this manner the peaks occur at 20–22% of total FeO, which is equivalent to about 15½% of total iron. The total iron content of industrial basic slags does not generally exceed this limit, and there is therefore no opportunity of observing the maximum under normal steelmaking conditions.

By plotting the results in a modified form it is possible to bring out other salient features. Thus, appropriate points of the curves of Fig. 17 are replotted in Fig. 18 to show how the distribution factor $(P_2O_5)/[P]$ varies with the lime/silica ratio for fixed FeO contents. When the FeO content is as low as 8% the rate of increase in the distribution factor is small below a lime/silica ratio of 3·5, but on increasing the ratio from 3·5 to 4·0 the distribution factor is doubled. A somewhat similar effect is observed with an FeO content of 10%, but when the FeO is increased to 12% the maximum rate of increase in the distribution factor occurs as the lime/silica ratio is increased from 2·4 to 2·8. This tendency is also observed in the curve for 14% of FeO, and in the curve drawn to pass through the points which correspond to the optimum FeO values in Fig. 17, but in both cases the rate of increase in the distribution factor as the lime/silica ratio is increased beyond 2·8 is fairly constant. At 16% of FeO, which corresponds to the maximum on the curve for a lime/silica ratio of 4·0 in Fig. 17, almost a linear relationship exists between $(P_2O_5)/[P]$ and $(CaO)/(SiO_2)$, but as the FeO content is increased still further there is a tendency for the rate of increase of the distribution factor to diminish as the lime/silica ratio is increased beyond 3·5. In fact, the curves for 20 and 22% of FeO indicate a reduction in the distribution factor in this range of lime/silica ratios, though it is considered probable that this effect is not genuine, but is to be attributed to experimental errors.

From a fuller treatment of the results, which is to be given later, there is reason to believe that the experimental errors are relatively high in this region. It seems probable that for the curves

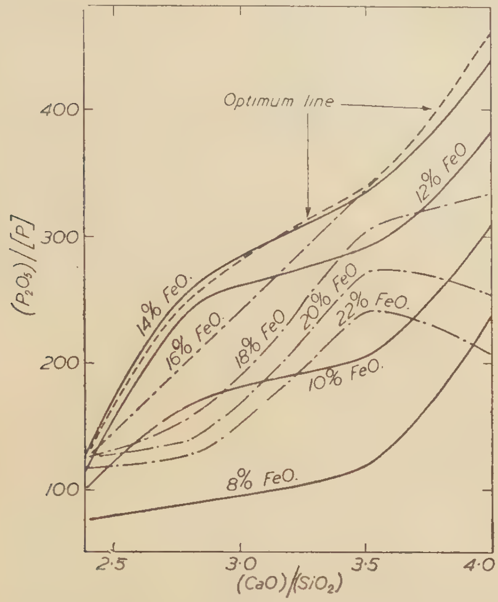


FIG. 18.—Relationship between $(CaO)/(SiO_2)$ and $(P_2O_5)/[P]$ Ratios.

corresponding to 20 and 22% of FeO respectively, increasing the lime/silica ratio beyond 3·5 causes little variation in the distribution factor.

In Fig. 19 the distribution factor has been

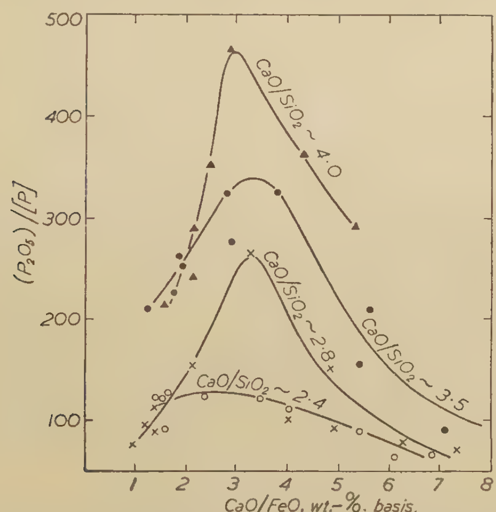


FIG. 19.—Relationship between $(CaO)/(FeO)$ and $(P_2O_5)/[P]$ Ratios.

plotted against the $(CaO)/(FeO)$ ratio. The experimental points obtained for a definite lime/silica ratio fall on a curve with a pronounced peak, which in all cases lies between $(CaO)/(FeO)$ ratios of about 3 and 4. Generally speaking, the $(CaO)/(FeO)$ ratios used in steelmaking are higher than this, and Fig. 19 makes it clear that in this range reduction in the $(CaO)/(FeO)$ ratio causes an increase in the distribution factor.

The final phosphorus content of the metal bears a definite relationship to the FeO content of the slag, and for each series the minimum phosphorus content corresponds to the peak of the curve in Fig. 17. Thus, series D, Fig. 20, is characteristic

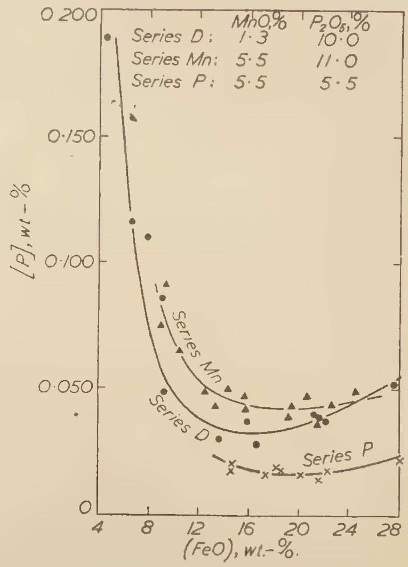


FIG. 20.—Relationship between (FeO) and [P].

and corresponds to the series with a lime/silica ratio of 3·5. As the FeO content of the slag is increased the phosphorus content of the metal falls off rapidly, reaching a minimum of 0·03% by weight at 14–16% by weight of FeO. As the FeO is increased still further, the phosphorus content of the metal increases, but at a relatively low rate. The general tendency occurs in all the series, as may be seen by referring to the results contained in Table I.

Effect of MnO.—In addition to the standard series containing 1·5% of MnO, special series of melts were carried out with a lime/silica ratio of 3·5, the Mn and MnX series each containing 5·5% of MnO, and the MnY series 11% of MnO. The results are plotted in Fig. 21. There is a progressive lowering of the peak with increasing MnO, the maximum values of the distribution factor being 332, 274, and 228 for 1·5, 5·5, and 11·0% of MnO, respectively. These values are almost directly proportional to the corresponding lime contents of 49, 43, and 41%, which suggests that the effect of MnO is merely that of dilution of the active constituents of the slag.

Effect of P_2O_5.—With a view to investigating the effect of P_2O_5, a special P series of melts was carried out in which the P_2O_5 content was reduced to 5·5% and, in order to maintain a comparable

viscosity, the MnO content was increased from 1·5 to 5·5%. The curve for series *P* is given in Fig. 22, together with those for series containing 10–11% of P_2O_5 with 1·5 and 5·5% of MnO, respectively. Comparison of the curves shows that the maximum value of the distribution factor $(P_2O_5)/[P]$ is almost exactly the same for the series containing 1·5% of MnO and 10–11% of

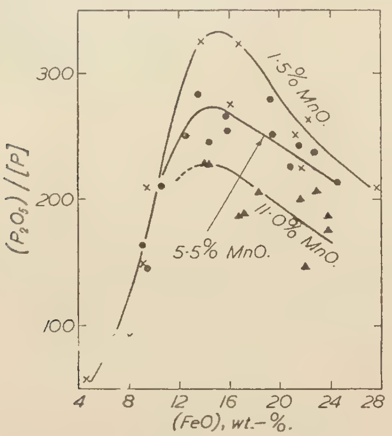


FIG. 21.—Effect of (MnO) upon $(P_2O_5)/[P]$.

P_2O_5 as for that containing 5·5% of MnO and 5·5% of P_2O_5. This, taken with the third curve, indicates that the effect of increasing the MnO from 1·5 to 5·5% is almost exactly counterbalanced, as far as the magnitude of the distribution factor is concerned, by decreasing the P_2O_5 from 11·0 to 5·5%. It will be seen that decreasing the (P_2O_5) in this way causes the point of maxi-

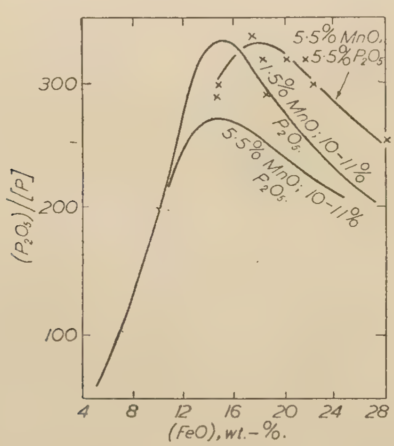


FIG. 22.—Effect of (P_2O_5) upon $(P_2O_5)/[P]$.

mum distribution factor to move from $14\frac{1}{2}$ to $17\frac{1}{2}$% of FeO. This effect is probably connected with the fact that P_2O_5 is one of the constituents involved in the phosphorus reaction.

The curves showing the variation of phosphorus in the metal with FeO in the slag for the three series of melts referred to have been plotted in Fig. 20. The series containing low (P_2O_5) is characterized by a low phosphorus content in the metal. For the two curves of Fig. 22 which show almost identical maximum values of $(P_2O_5)/[P]$, the corresponding minimum values for phosphorus in the metal are 0·032 and 0·016% respectively. The fact that low (P_2O_5) in the slag leads to low phosphorus in the metal is in agreement with general experience.

Effect of Al_2O_3.—Special alumina melts *Al* 1–5 and *Al* 6–10 have been carried out with lime/silica ratios of 4·0 and 3·5 respectively, the alumina content being about 8·0% in each case. The curves showing the variation of $(P_2O_5)/[P]$ with FeO content are plotted with those for similar lime/silica ratio, but normal

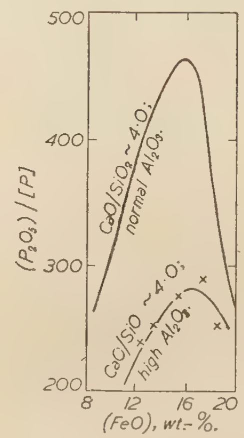


FIG. 23.

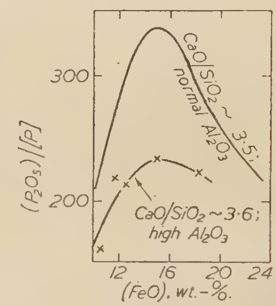


FIG. 24.

FIGS. 23 and 24.—Effect of (Al_2O_3) upon $(P_2O_5)/[P]$.

Al_2O_3 content, in Figs. 23 and 24 respectively. For each lime/silica ratio the effect of increasing the alumina content of the slag is to cause a marked decrease in the distribution factor $(P_2O_5)/[P]$. This decrease is relatively greater than was observed with MnO and is difficult to explain on a basis of simple dilution. Although there is no direct evidence at this stage, it seems likely that the alumina reduces the amount of lime available for dephosphorization in somewhat the same manner as does silica, but when the results are discussed in more detail later it will be seen that the relationship developed for slags of normal alumina content is also valid for alumina contents of up to 8%, and that the apparent difference in behaviour is not significant from a statistical point of view.

Treatment of Results.

Since the ultimate object of this work was to derive some method of correlating the results in a quantitative manner capable of general application, the experimental data have been studied from several different points of view. When all the results were plotted together to show the effect of (FeO) upon the distribution factor $(P_2O_5)/[P]$, it was found possible to draw smooth

curves through points corresponding to slags of approximately equal lime content (Fig. 25). This was also true when (CaO) was plotted against $(P_2O_5)/[P]$, but the scatter of the points was rather more marked in this case. The curves reproduced in Fig. 25 enable the effects of (FeO) and of (CaO) upon the distribution factor to be more readily understood. Thus, for slags containing a given percentage of lime, the distribution factor increases progressively with the (FeO) content. Furthermore, the higher the lime content of the slag, the greater is the increase in distribution factor for a given increase in (FeO), so that

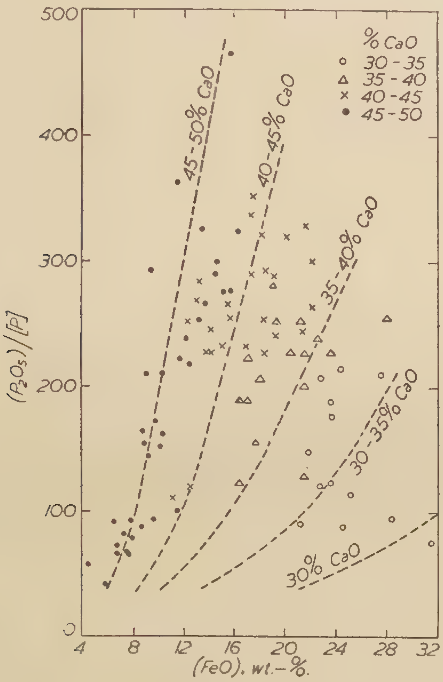


FIG. 25.—Effect of (CaO) and (FeO) upon $(P_2O_5)/[P]$.

for a definite (CaO + FeO) content, better results are obtained with low (FeO) and high (CaO). Again, it may be seen from Fig. 25 that for slags containing a given percentage of (FeO), the distribution factor increases continuously with the (CaO) content.

The curves drawn in Fig. 25 cannot be regarded as giving a truly quantitative picture, but classification of the results is more simple than on the basis of lime/silica ratio. Thus the results of melts with slags of varying (SiO_2), (MnO), (P_2O_5), and (Al_2O_3) contents no longer need separate treatment, and it is clear that the value of the distribution factor for a given slag–metal system is determined almost entirely by the (CaO) and (FeO) contents of the slag.

The conclusions drawn from this method of plotting appear at first sight to conflict with those based on the method in which the results are grouped according to the lime/silica ratio. For a slag of given lime/silica ratio and fixed content of fluxes, any increase in (FeO) must cause a proportional decrease in the lime content and *vice versa*, whereas the curves of Fig. 25 indicate the effect of (CaO) and (FeO) when there is no such restriction.

Many attempts have been made by other workers to correlate data obtained from steelworks practice, and among them may be mentioned those due to Whiteley [10] and to McCance.[11] Whiteley plotted the distribution factor (P)/[P] on a weight per cent basis against a "basicity index" which he defined as:

$$\text{Basicity index} = \frac{FeO + MgO + CaO + MnO - 3P_2O_5}{SiO_2},$$

using molecular ratios in all cases. The results of the present work have been plotted in this way and are given in Fig. 26. The experimental

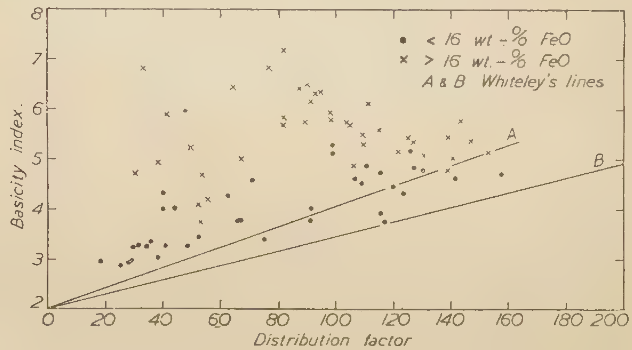


FIG. 26.—Experimental Data Plotted by Whiteley's Method.

points cannot be represented by a straight-line relationship, but the scatter increases with increasing basicity index, so that all the points are contained within a triangular area with apex at basicity index approximately 2 and distribution factor zero. Reference to Whiteley's original paper revealed that the scatter of his experimental results also increased with the basicity index, and that his points fell within a triangular area in the manner observed in the present work. Further consideration of the results of the present work shows that the behaviour of slags containing low or normal (FeO) can be reasonably represented by a straight line based on Whiteley's method. In order to illustrate this point the results for slags containing less than 16% of FeO are represented in Fig. 26 by black circles and those corresponding to higher (FeO) values by crosses. Although Whiteley's method cannot be applied satisfactorily to the wide range of slag compositions employed here, it seems likely that better agreement is to be expected when it is applied to industrial slags, where the range of compositions generally encountered is much smaller.

McCance has defined the dephosphorizing factor of a slag as :

$$F_P = \frac{1}{[P]} \cdot \frac{(P_2O_5)}{(FeO) + (P_2O_5)},$$

and has plotted F_P against the lime content of a number of industrial slags, obtaining a straight-line relationship with relatively little scatter of the points. The factor becomes zero at 32% of (CaO), indicating the absence of dephosphorization with slags containing lower proportions of lime. When the present results are plotted in this manner, no such linear relationship is obtained, as will be seen from Fig. 27; indeed, dephosphorizing factors of about 400 are possessed by slags with lime contents ranging from $32\frac{1}{2}$ to 50%. Closer inspection shows that most of the results for slags containing 13% or less of (FeO) lie well below the line drawn by McCance. Similarly, most of the points which lie well above

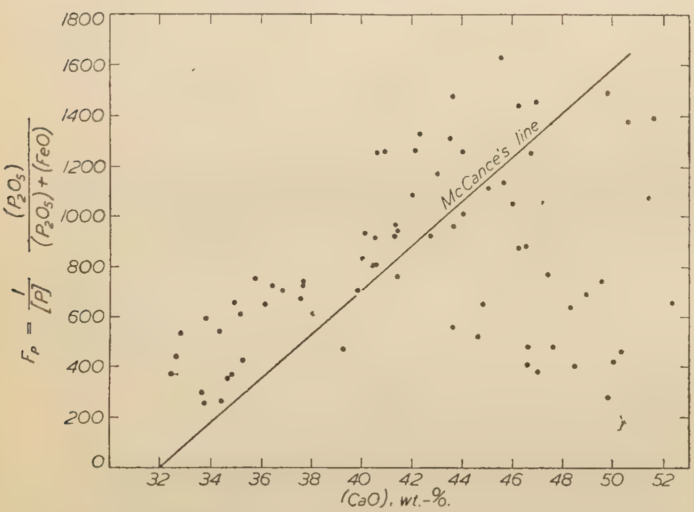


Fig. 27.—Experimental Data Plotted by McCance's Method.

the line are characterized by high (FeO) content. McCance's line can be regarded as giving a reasonably good representation of the behaviour of slags containing from 13 to 19% of (FeO) and also of some of the high-(FeO) slags containing only a small proportion of lime. The introduction of (FeO) into the dephosphorizing factor was with the intention of compensating for the effect of (FeO) variations in the slag; the present results show that any such compensation is confined to a limited range of slag compositions and cannot be regarded as of general application.

The effect of variations in (FeO) content upon the dephosphorizing factor as defined by McCance can be shown more readily by plotting F_P against (FeO). This has been done in Fig. 28, and smooth curves have been drawn through points corresponding to slags of approximately the same lime contents. According to McCance, for each value of the dephosphorizing factor there is a unique lime content, but Fig. 28 makes it plain that when this treatment is applied to a wider range of slag compositions it is possible to obtain the same dephosphorizing factor with different lime contents, and that for a given lime content the dephos-

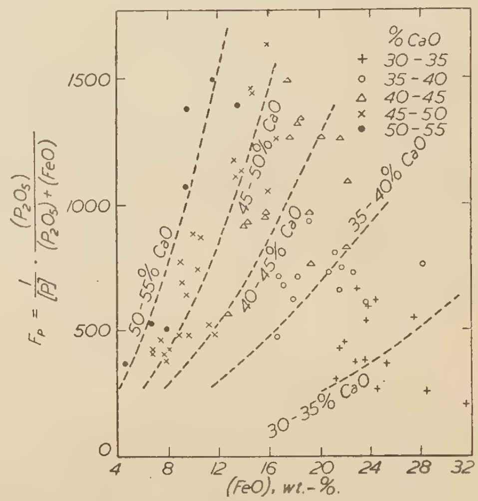


Fig. 28.—Effect of (FeO) and (CaO) upon the Dephosphorizing Factor.

phorizing factor is governed by the (FeO) content of the slag. The general characteristics of Fig. 28 are remarkably similar to those of Fig. 25, in which $(P_2O_5)/[P]$ was plotted against (FeO).

In a recent paper, Jackson [14] found that when

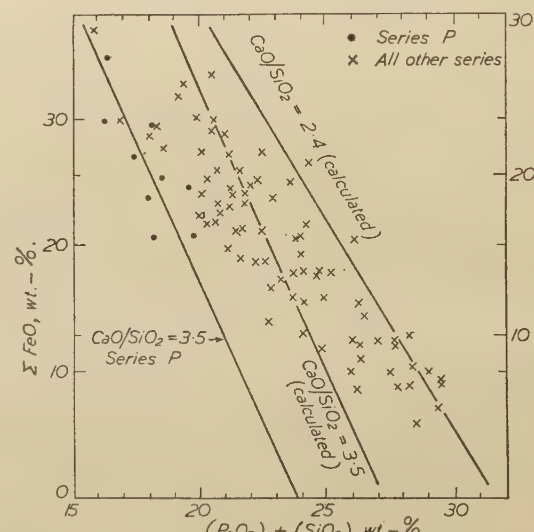


Fig. 29.—Experimental Data Plotted by Jackson's Method.

slag samples were taken at well-defined stages in the steelmaking process, it was possible to draw curves showing direct relationships between the total iron content of the slag and the sum of the (P_2O_5) and (SiO_2) contents. Slightly different curves applied for samples taken (1) half-an-hour

before slagging-off, (2) during slagging-off, and (3) during tapping. The results obtained in the present work have been plotted on this basis in Fig. 29 and the scatter of the points is considerable. The results for any one series of melts with a fixed lime/silica ratio may be fairly represented by a straight line, but increasing the lime/silica ratio or decreasing the total flux content causes the line to move to the left. All the slags examined by Jackson contained between 45 and 50% of lime, and most fell within the limits 47–48%. The slope of the line obtained by Jackson can be explained almost quantitatively if it is assumed that the lime was maintained at a constant value and that any increase in the total iron content of the slag was at the expense of the ($P_2O_5 + SiO_2$) content. These assumptions are most nearly justified by the results given in Table VII. and illustrated in Fig. 10 of Jackson's paper, where the sum of FeO, Fe_2O_3, SiO_2, and P_2O_5 lies within the limits 37·29 and 39·76%, with a mean value of 38·88%. Each 1% of (P_2O_5 + SiO_2) could replace or be replaced in the slag by 1% of FeO or of Fe_2O_3, and the corresponding values of iron would be 0·78 and 0·70% respectively. In Jackson's slags the quantities of FeO and Fe_2O_3 are approximately equal, so that 1% of ($P_2O_5 + SiO_2$) would be replaced by approximately 0·74% of iron in the slag. As closely as can be measured from the small Fig. 10 in Jackson's paper, the slope of the line is approximately 0·76. In (Jackson's) Figs. 9 and 11 the curvature of the lines is more marked, but quite a reasonable representation of the points is possible in each case by a straight line with slope about 0·75.

The scatter of our results when plotted in this manner can also be explained in terms of the dilution effect. Thus, for a given series of melts, the lime/silica ratio and the content of (P_2O_5) and other fluxes was maintained constant and the lime/silica content was successively replaced by (FeO). Taking the low-phosphorus series, *P*, as an example, the (P_2O_5) content was approximately 5·5% in all cases, whilst the sum of the MgO, MnO, and Al_2O_3 contents was about 12%. The sum of FeO, CaO, and SiO_2, therefore, came to 82·5% for all the slags, and for a slag containing no FeO, the corresponding SiO_2 would be 18·3%, as the lime/silica ratio for this series was 3·5. Hence the sum of the (SiO_2) and (P_2O_5) contents at zero (FeO) would be 23·8%. If it be remembered that when the (FeO) content is increased, the (CaO + SiO_2) content is decreased by a similar amount, and that the lime/silica ratio is constant for a given series, it will be seen that, in order to increase the (SiO_2) and therefore the ($SiO_2 + P_2O_5$) content of the slag by 1%, the (FeO) must be reduced by $(m + 1)$%, where m is the lime/silica ratio. This means that the slope of the line is $(m + 1)$ when (FeO) is plotted against ($P_2O_5 + SiO_2$) and in the case under consideration this becomes 4·5, so that the equation of the straight line representing the *P* series is given by :

$$(\mathrm{FeO}) = 4{\cdot}5\,[23{\cdot}8 - (\mathrm{P_2O_5} + \mathrm{SiO_2})]$$

or :

$$\text{Total Fe} = 3{\cdot}5\,[23{\cdot}8 - (\mathrm{P_2O_5} + \mathrm{SiO_2})].$$

This line has been drawn in Fig. 29 and is a reasonable representation of the low-phosphorus series, the experimental points of which are indicated by black circles. The other two lines reproduced in Fig. 29 were calculated for the series *C* and *D* with lime/silica ratios 2·4 and 3·5 respectively, and the agreement with the experimental points is good. These lines illustrate the fact that under our conditions the slope of the line is determined by the lime/silica ratio, and that for a given lime/silica ratio the position of the line is governed by the sum of the fluxes present.

In carrying out these calculations it was assumed that all the iron in the slag was present as FeO, but it can be shown that the error involved in the present case by treating Fe_2O_3 as FeO is of the order of only 1 or 2%.

The treatment which has been given here shows that the relationship observed by Jackson has no such physico-chemical significance as he suggested, but is due to the effect of dilution under the strict conditions of slag control exercised in the particular works.

Of the methods which have been developed in attempts to place the phosphorus reaction on a quantitative basis, that due to Schenck and Riess [12] seems to be unduly complicated and, even so, involves an empirical correction factor, whilst those which are claimed as only empirical relationships based on practical experience have been shown above to be very limited in their application. An attempt will therefore be made to throw light on the nature of the phosphorus reaction and to give a treatment which is applicable to the wide range of slag compositions used in this work.

It is widely accepted that the simplest form of the equation representing the oxidation of phosphorus in the metal phase is :

$$2\mathrm{P} + 5\mathrm{FeO} \rightleftharpoons \mathrm{P_2O_5} + 5\mathrm{Fe} \quad . \quad . \quad . \quad (1)$$

and that the equilibrium constant for this reaction is given by :

$$k' = \frac{[\mathrm{P_2O_5}]}{[\mathrm{P}]^2[\mathrm{FeO}]^5}.$$

In the case of a heterogeneous system consisting of slag and metal phases, another constant, k, can be written :

$$k = \frac{(\mathrm{P_2O_5})}{[\mathrm{P}]^2(\mathrm{FeO})^5}.$$

TABLE II.—*Values of* k *Calculated on the Basis of* (a) *Analytically Determined* (FeO) *and* (b) *the* FeO *Equivalent of* (ΣFe).

Melt No.	Wt.-% Basis.						Mol.-% Basis.			
	ΣCaO.	Log ΣCaO.	Calc. on Analytical FeO.		Calc. on ΣFe Expressed as FeO.		ΣCaO.	Log ΣCaO.	$k \times 10^5$.	Log k + 5.
			$k \times 10^5$.	Log k + 5.	$k \times 10^5$.	Log k + 5.				
*A*5	34·4	1·537	10·6	1·028	3·9	0·592	40·3	1·605	2·4	0·388
*A*6	43·0	1·634	1866·0	3·271	417·7	2·621	48·9	1·689	416·3	2·620
*A*7	34·6	1·539	17·7	1·048	5·5	0·743	40·4	1·606	4·2	0·619
*A*8	38·0	1·580	184·2	2·265	66·9	1·825	41·9	1·622	52·8	1·723
*A*10	47·6	1·678	1060·0	3·025	304·3	2·483	53·4	1·727	291·7	2·465
*A*11	50·0	1·699	1825·8	3·262	495·8	2·695	55·8	1·746	543·0	2·735
*A*12	50·0	1·699	3399·1	3·532	993·3	2·997	56·2	1·749	944·1	2·975
*A*13	45·6	1·659	1475·5	3·170	445·1	2·649	52·4	1·719	361·5	2·558
*A*14	33·7	1·528	5·8	0·763	2·8	0·444	39·7	1·598	1·3	0·105
*A*15	30·4	1·483	3·0	0·473	1·3	0·121	35·4	1·548	0·7	−0·161
*A*16	46·6	1·668	527·3	2·722	125·8	2·100	52·7	1·721	137·7	2·139
*A*17	49·5	1·695	2048·0	3·312	1409·7	3·150	54·8	1·738	573·2	2·758
*B*1	48·5	1·686	2036·7	3·310	538·9	2·732	53·7	1·730	565·0	2·752
*B*2	46·5	1·668	3242·8	3·511	1074·4	3·031	51·6	1·712	894·8	2·952
*B*3	50·3	1·702	3125·0	3·496	1201·3	3·080	55·2	1·742	896·4	2·953
*C*1	34·8	1·542	24·9	1·396	11·5	1·061	39·6	1·597	5·4	0·728
*C*2	35·2	1·547	40·2	1·604	18·8	1·275	39·7	1·598	10·8	1·034
*C*3	39·2	1·593	131·2	2·117	45·3	1·656	44·0	1·642	39·4	1·595
*C*4	44·6	1·649	757·1	2·879	371·8	2·570	49·4	1·693	210·6	2·324
*C*5	46·6	1·668	3244·6	3·511	788·2	2·897	50·4	1·702	1033·0	3·014
*C*6	47·0	1·672	1732·3	3·238	661·3	2·820	51·3	1·710	538·0	2·731
*C*7	43·6	1·640	516·0	2·713	188·6	2·277	48·6	1·685	136·8	2·136
*C*8	47·8	1·679	1595·9	3·204	843·6	2·926	52·4	1·718	472·8	2·675
*C*9	49·8	1·698	2851·7	3·455	1102·5	3·041	53·8	1·730	846·5	2·928
*C*10	33·6	1·526	21·4	1·330	12·3	1·090	36·6	1·563	6·4	0·805
*C*11	32·4	1·511	23·2	1·366	11·0	1·041	36·4	1·560	6·0	0·778
*D*1	40·4	1·606	147·4	2·167	54·0	1·732	46·6	1·667	35·7	1·552
*D*2	37·6	1·575	123·0	2·090	56·3	1·751	42·0	1·623	33·6	1·527
*D*3	46·0	1·663	733·3	2·865	207·3	2·316	51·7	1·713	187·7	2·273
*D*4	40·9	1·612	135·4	2·130	48·0	1·681	45·7	1·660	35·8	1·554
*D*5	46·7	1·669	917·2	2·962	261·9	2·418	52·8	1·722	244·1	2·388
*D*6	51·6	1·713	2332·9	3·367	610·6	2·786	56·4	1·750	688·7	2·838
*D*7	58·1	1·764	6320·5	3·801	1717·7	3·236	61·0	1·784	2178·0	3·338
*D*8	56·1	1·749	2726·3	3·436	845·8	2·927	60·6	1·781	823·3	2·916
*D*9	48·9	1·689	3045·6	3·484	718·9	2·857	55·3	1·743	802·6	2·905
*D*11	54·9	1·740	16641·5	4·220	4230·8	3·626	59·5	1·774	5099·0	3·708
*D*12	51·4	1·711	6510·8	3·814	1411·0	3·149	57·4	1·758	1784·0	3·252
*D*13	34·3	1·535	25·2	1·401	9·5	0·978	40·3	1·606	5·5	0·742
*E*1	41·3	1·616	306·3	2·486	96·1	1·983	49·0	1·690	65·6	1·817
*E*2	44·0	1·644	719·7	2·857	173·8	2·241	50·7	1·704	174·6	2·242
*E*3	37·2	1·571	53·1	1·725	16·5	1·218	44·2	1·644	11·1	1·047
*E*4	45·5	1·658	1755·4	3·246	371·7	2·571	53·3	1·726	391·3	2·593
*E*5	49·8	1·698	4935·9	3·694	1041·0	3·017	56·5	1·752	1235·0	3·092
*E*6	50·0	1·704	9450·7	3·975	1950·0	3·290	56·7	1·753	2462·0	3·391
*E*7	41·4	1·617	176·6	2·248	46·2	1·665	48·9	1·690	37·9	1·579
*Mn*4	37·6	1·575	129·4	2·111	40·4	1·606	44·2	1·645	28·3	1·452
*Mn*6	47·4	1·676	3916·0	3·593	960·9	2·983	54·4	1·735	920·6	2·964
*Mn*7	48·3	1·684	2274·0	3·356	612·2	2·787	54·3	1·734	582·9	2·766
*Mn*10	43·6	1·640	635·8	2·804	145·0	2·161	50·9	1·706	142·8	2·155
*Mn*11	40·5	1·608	150·6	2·179	76·6	1·884	47·0	1·672	34·5	1·537
*Mn*12	40·0	1·602	218·1	2·339	70·4	1·848	47·1	1·673	59·4	1·774
*Mn*13	44·0	1·644	1747·2	3·243	278·9	2·446	52·4	1·720	371·0	2·569
*MnX*1	35·1	1·545	50·6	1·703	17·8	1·250	42·1	1·623	10·4	1·018
*MnX*2	40·1	1·603	282·0	2·450	76·4	1·883	47·4	1·675	61·5	1·789
*MnX*3	42·7	1·630	851·8	2·930	188·7	2·277	50·8	1·706	178·0	2·251
*MnX*4	36·4	1·561	92·0	1·964	26·0	1·415	43·7	1·640	18·6	1·270
*MnX*5	41·4	1·617	612·4	2·787	151·0	2·179	48·9	1·690	134·6	2·129
*MnX*7	46·2	1·665	2664·3	3·425	522·9	2·719	54·2	1·733	598·7	2·777
*MnX*8	45·2	1·653	1585·2	3·201	358·8	2·555	53·2	1·725	345·8	2·539

(Continued.)

TABLE II.—*Continued.*

Melt No.	Wt.-% Basis.						Mol.-% Basis.			
	ΣCaO.	Log ΣCaO.	Calc. on Analytical FeO.		Calc. on ΣFe Expressed as FeO.		ΣCaO.	Log ΣCaO.	$k \times 10^5$.	Log k + 5.
			$k \times 10^5$.	Log k + 5.	$k \times 10^5$.	Log k + 5.				
*MnY*1	32·6	1·513	37·9	1·579	12·3	1·090	39·4	1·595	7·5	0·875
*MnY*2	32·8	1·516	43·7	1·641	14·6	1·164	39·4	1·595	8·7	0·940
*MnY*3	36·8	1·566	190·5	2·281	56·3	1·751	43·8	1·641	39·2	1·594
*MnY*4	37·5	1·574	229·2	2·360	56·4	1·751	44·5	1·648	47·2	1·674
*MnY*5	40·5	1·608	890·9	2·950	202·2	2·305	48·3	1·684	184·1	2·265
*MnY*6	34·8	1·542	80·3	1·905	26·0	1·415	41·9	1·622	16·4	1·215
*MnY*7	33·8	1·529	58·5	1·767	18·0	1·255	40·3	1·605	12·2	1·085
*MnY*10	36·1	1·558	95·1	1·978	26·6	1·425	42·9	1·632	19·3	1·285
*MnY*11	39·8	1·600	280·3	2·447	75·1	1·876	47·2	1·672	58·4	1·766
*MnY*12	41·3	1·616	859·3	2·934	205·9	2·314	48·3	1·685	190·4	2·280
*P*1	35·7	1·553	66·4	1·822	22·3	1·348	42·3	1·626	14·1	1·149
*P*2	42·0	1·623	309·7	2·491	71·4	1·854	49·4	1·693	69·4	1·842
*P*3	46·2	1·665	2185·0	3·340	392·2	2·593	52·7	1·721	539·9	2·732
*P*4	43·6	1·640	1325·0	3·124	277·4	2·443	50·0	1·698	315·4	2·499
*P*5	43·5	1·639	847·6	2·928	188·0	2·274	50·4	1·702	197·2	2·295
*P*6	42·3	1·626	746·3	2·873	151·9	2·182	49·6	1·695	171·4	2·234
*P*7	42·1	1·624	613·2	2·788	139·2	2·143	49·1	1·690	137·2	2·137
*P*8	46·9	1·671	2429·0	3·386	421·0	2·624	53·8	1·730	599·8	2·778
*P*9	40·6	1·609	499·1	2·698	98·3	1·993	47·7	1·677	111·9	2·049
*Al*1	42·4	1·627	332·9	2·522	86·9	1·939	48·8	1·688	50·6	1·704
*Al*2	43·8	1·642	605·5	2·782	172·1	2·236	50·6	1·703	141·6	2·151
*Al*3	48·6	1·687	1926·6	3·285	439·3	2·643	57·1	1·756	423·5	2·627
*Al*4	48·4	1·685	1516·7	3·181	276·0	2·441	57·0	1·755	334·7	2·525
*Al*5	46·0	1·663	939·6	2·973	185·6	2·270	53·0	1·723	229·3	2·360
*Al*6	42·3	1·626	260·9	2·417	80·8	1·907	49·4	1·693	59·9	1·778
*Al*7	44·5	1·648	742·0	2·870	196·6	2·295	51·3	1·710	175·6	2·244
*Al*8	47·8	1·679	2067·7	3·316	472·9	2·675	56·3	1·750	458·0	2·661
*Al*9	48·7	1·688	2178·5	3·338	531·3	2·725	57·2	1·757	481·5	2·683
*Al*10	47·8	1·679	1566·3	3·195	304·9	2·484	56·1	1·748	334·1	2·524

This involves the assumption that the $[P_2O_5]$ and [FeO] in the metal are directly proportional to the total (P_2O_5) and to the (FeO) contents of the slag, respectively. In view of the known affinity of CaO for P_2O_5 in the formation of a stable phosphate, it seemed logical to investigate the effect of (CaO) upon the constant k. Accordingly the values of k for all the melts have been calculated on the basis of (*a*) the analytically determined ferrous oxide of the slag and (*b*) the FeO equivalent of the total iron in the slag, both on a weight per cent basis; the results are given in Table II. and are plotted graphically against the corresponding total lime contents in Figs. 30 and 31. In both cases the form of the curve giving a fair representation of the experimental points suggests a relationship of the type $y = cx^n$, and this was also true when the constant was calculated on the basis of molecular percentages. If a power law is valid, a straight-line relationship should be obtained by plotting the logarithm of the constant against the logarithm of the total lime content of the slag. This was found to be the case, and the results on a weight per cent basis are given in Figs. 32 and 33. Using the method of least squares, the straight line which fitted best the

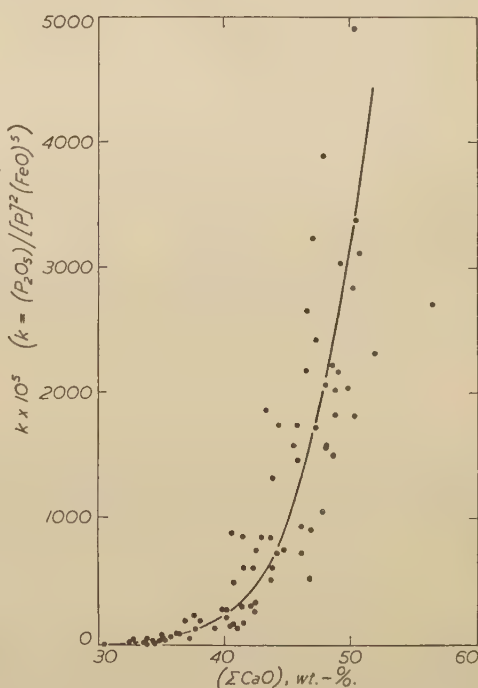


FIG. 30.—Effect of Lime upon k, using analytically determined (FeO).

results of all except the high-alumina series was found to be :

$$\text{Log } k = 12{\cdot}06 \log \Sigma\text{CaO} - 21{\cdot}93,$$

and the correlation coefficient was 0·944. For the ten results of the high-alumina series, the straight line was given by :

$$\text{Log } k = 13{\cdot}24 \log \Sigma\text{CaO} - 24{\cdot}02$$

and the correlation coefficient was 0·979. In view of the fact that all the results for the high-alumina series fell below the line representing the other 78 results, but within the experimental error, it was considered desirable to apply a statistical

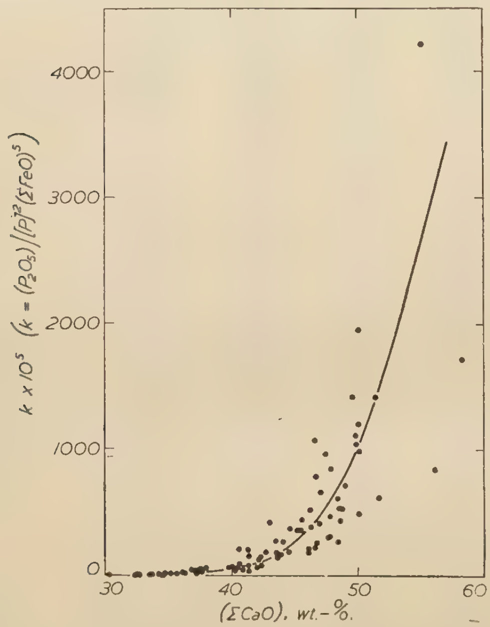


FIG. 31.—Effect of Lime upon k, using ΣFeO.

test to determine whether this apparent difference in behaviour of the high-alumina series was significant or not.

Fisher [15] has devised a method for determining if the difference between two correlations is significant by transforming the correlation coefficient r into a quantity z given by :

$$z = \tfrac{1}{2} \log_e \left(\frac{1 + r}{1 - r}\right).$$

For a number of observations N, greater than 3, the standard error of z is $1/\sqrt{N - 3}$, and the standard error of the difference between two z's is :

$$\sqrt{\frac{1}{N_1 - 3} + \frac{1}{N_2 - 3}},$$

where N_1 and N_2 are the numbers of pairs in the two samples. If the difference between the two z's is greater than twice the standard error, the difference is significant.

For the melts of normal alumina content, $N_1 = 78$ and $r_1 = 0{\cdot}944$, so that $z_1 = 1{\cdot}773$, and for the high-alumina series, $N_2 = 10$, $r_2 = 0{\cdot}979$, and $z_2 = 2{\cdot}275$. The standard error of the difference in z corresponding to these figures is 0·395, and the difference between the two correla-

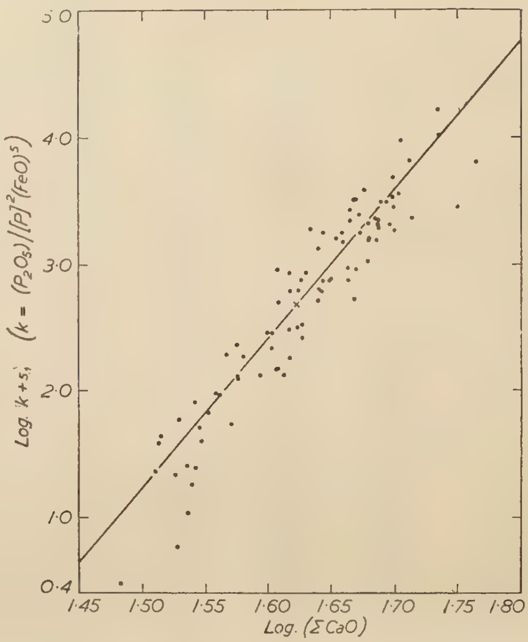


FIG. 32.—Relationship between log (ΣCaO) and log k + 5.

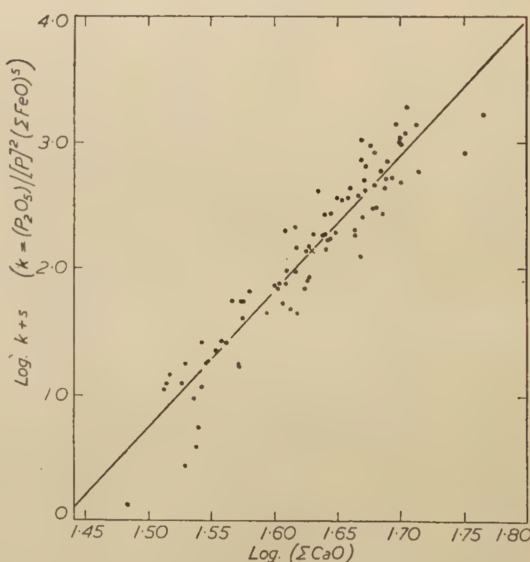


FIG. 33.—Relationship between log (ΣCaO) and log k + 5, using ΣFeO.

tions will be significant if $(z_2 - z_1)$ is greater than 0·790. In fact, $(z_2 - z_1) = 0{\cdot}502$, and it must therefore be concluded that there is no significant difference between the high- and low-alumina series.

In view of this it was decided to treat all the 88 results together, and it was found that they could be represented by the straight line :

$$\text{Log } k = 11{\cdot}80 \log \Sigma\text{CaO} - 21{\cdot}51 \quad . \quad . \quad (4)$$

drawn in Fig. 32, and that the correlation coefficient was 0·939.

Values of k were also calculated on the basis of total iron converted to FeO, and the results, together with the best-fit straight line, are given in Fig. 33. The equation of the line is :

$$\text{Log } k = 10{\cdot}78 \log \Sigma\text{CaO} - 20{\cdot}41 \quad . \quad . \quad (5)$$

and the correlation coefficient was 0·932.

Using the FeO contents experimentally determined, the values of k were calculated on a molecular per cent. basis. It was found that the 78 results which excluded the high-alumina series could be represented by the straight line :

$$\text{Log } k = 13{\cdot}99 \log \Sigma\text{CaO} - 26{\cdot}51 \quad . \quad . \quad (6)$$

the correlation coefficient being 0·949. For the high-alumina series the best-fit straight line was given by :

$$\text{Log } k = 11{\cdot}73 \log \Sigma\text{CaO} - 22{\cdot}95 \quad . \quad . \quad (7)$$

and the correlation coefficient was 0·936.

The significance test was applied, but it was found that $(z_1 - z_2) = 0{\cdot}117$, whereas it must exceed 0·790 in order to be statistically significant.

Since there was no justification for dealing with the high-alumina series separately, all 88 results were considered together. The best-fit straight line corresponded to the equation :

$$\text{Log } k = 13{\cdot}65 \log \Sigma\text{CaO} - 25{\cdot}97 \quad . \quad . \quad (8)$$

and the correlation coefficient was 0·938.

Before making use of the straight-line relationship thus obtained, it is desirable to consider certain points regarding the (FeO) values used in evaluating the constant k. Thus, Chipman [16] found that the oxygen content of the metal was directly proportional to the analytically determined (FeO) content of the quenched slag, and he concluded that the Fe_2O_3 present in the liquid state must be in a combined form. On this basis it would seem more correct to use the analytically determined (FeO) rather than the FeO equivalent of the total iron, but it should be remembered that the linear relationship between log k and log ΣCaO is based on experimental results and is empirical in nature. There is little difference between the correlation in the two cases and therefore, from the practical point of view, either free or total (FeO) can be used, at least at 1585° C. One advantage of using the total (FeO) value is that it is independent of the rate of cooling of the slag sample, whereas, in order to make use of Fig. 32, the slag sample must be rapidly quenched in water so that the $FeO \longrightarrow Fe_2O_3$ change may be suppressed.

It cannot be too strongly emphasized that the linear relationship between log k and log ΣCaO is empirical in nature and has no direct theoretical basis. As will be shown later when considering the effect of slag constitution, the linear relationship indicates that the free lime in basic slags must be directly related to the total lime content.

The linear relationship between log k and log ΣCaO is in keeping with the peak previously observed on the curve between the distribution factor $(P_2O_5)/[P]$ and the (FeO) content of the slag, and by assuming the appropriate values of k it is possible to calculate the precise form of this curve.

Thus, for the low-phosphorus series P, the average content of fluxes was 5·42% of P_2O_5, 2·68% of Al_2O_3, 5·61% of MnO, and 4·22% of MgO, whilst the average lime/silica ratio was 3·4. The sum of the lime, silica, and total FeO was

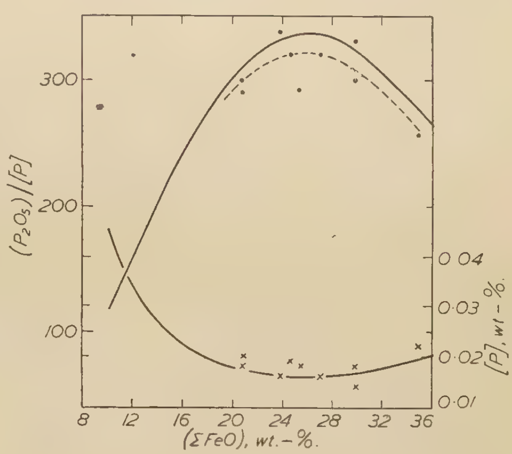


FIG. 34.—Calculated Curves for Series P.

therefore 82% of the slag, and as the amount of total FeO was increased, 1·29% of FeO was replaced by 1·0% of lime and 0·29% of silica. By incorporating these relationships in equation (5) we obtain :

$$\text{Log } [P] = 10{\cdot}572 - 2{\cdot}5 \log \Sigma\text{FeO} - 5{\cdot}39 \log \Sigma\text{CaO} \quad . \quad . \quad . \quad (9)$$

Using this equation, the values of the phosphorus content of the metal, and also of the distribution factor $(P_2O_5)/[P]$, for various total FeO contents, have been calculated, and the results are plotted in Fig. 34. The experimental points for the low-phosphorus series P have also been plotted in Fig. 34 and show that the positions of the experimental curves agree reasonably well with those calculated from equation (9).

Equations (4) and (5) may be used to calculate slag compositions required for control purposes at 1585° C. Thus, equation (4), based on the use

of the analytically determined (FeO), can be rewritten :

$$\text{Log (FeO)} = 4{\cdot}302 - 2{\cdot}360 \log \Sigma(\text{CaO}) - 0{\cdot}4 \log [\text{P}] + 0{\cdot}2 \log (\text{P}_2\text{O}_5) \quad . \quad (10)$$

and equation (5), based on the FeO equivalent of the total iron becomes :

$$\text{Log } \Sigma(\text{FeO}) = 4{\cdot}082 - 2{\cdot}156 \log \Sigma(\text{CaO}) - 0{\cdot}4 \log [\text{P}] + 0{\cdot}2 \log (\text{P}_2\text{O}_5) \quad . \quad (11)$$

These equations have been used to evaluate the values. Thus, referring to the curves based on the FeO equivalent of the total iron, it will be seen that the required degree of dephosphorization will be produced by slags containing 9% of (P_2O_5) and 17% of (ΣFeO), if the total lime content is held at 45%.

It must be borne in mind when using equations (10) and (11) and Figs. 35–38, which were derived from them, that they are all based on experimental results obtained under equilibrium con-

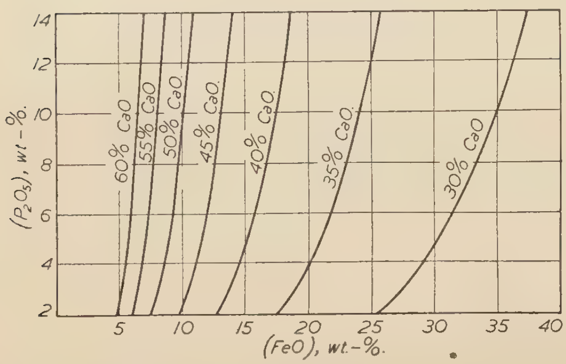


Fig. 35.

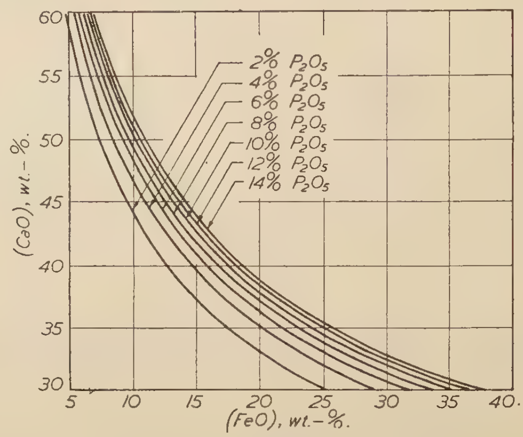


Fig. 36.

Figs. 35 and 36.—Relationship between (FeO), (CaO), and (P_2O_5) to give 0·05% of Phosphorus in the Steel at 1585° C. (Based on Fig. 32.)

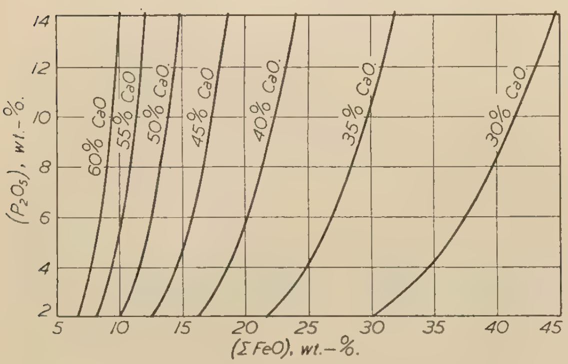


Fig. 37.

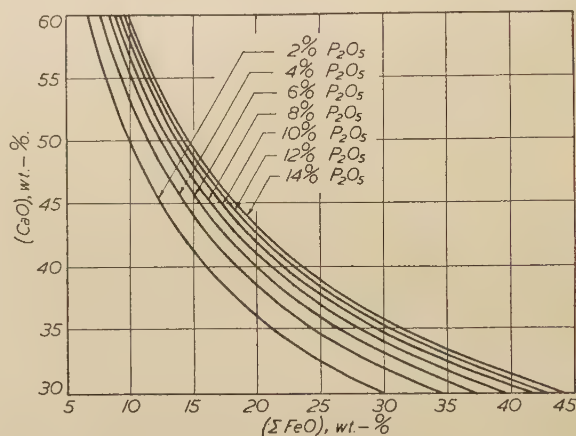


Fig. 38.

Figs. 37 and 38.—Relationship between (ΣFeO), (CaO), and (P_2O_5) to give 0·05% of Phosphorus in the Steel at 1585° C. (Based on Fig. 33.)

lime and iron oxide contents necessary to reduce the phosphorus in the metal to 0·05% for different (P_2O_5) contents of the slag, and the results are plotted in Figs. 35–38. The curves of Figs. 35 and 37 show how the (P_2O_5) determined the (FeO) or Σ(FeO) necessary to reduce [P] to 0·05% when the lime was maintained at certain specified values. Similarly, Figs. 36 and 38 show the corresponding relationships between the lime and iron oxide contents when the (P_2O_5) is held constant at certain values.

ditions at 1585° C., and agreement should not be expected with practical results obtained under any other conditions.

It is unfortunate that results obtained under steelmaking conditions are not available in sufficient numbers to test the relationships put forward in this paper. When slag analyses are published, it frequently happens that they are unaccompanied by satisfactory temperature measurements or even that the analysis of the

corresponding metal is omitted. Recently, Zea [13] has given the analyses for 29 melts, but so few of these were carried out in the range 1575–1595° C. that they afford no real test of the present deductions. Until the present work has been extended to other temperatures, it would be unwise to speculate as to the quantitative effect of temperature upon the relationship between log k and log ΣCaO, nor is it possible to determine whether there is any systematic difference between the temperatures measured in the steel bath and those determined in the small laboratory unit. It would seem to be desirable that results obtained under industrial conditions should be dealt with in the manner described above, but it may be difficult to determine the slope of the line with accuracy, as, in a given plant, the lime content of the slag is not generally varied over a wide range.

Since Zea claimed that of the methods available, that due to Schenck and Riess predicted most closely the actual phosphorus contents of his 29 melts, the possibility of comparing this method with that developed in the present paper was considered. It was found that the method was so laborious that the time taken for a single result was some 20–30 min., so that to apply it to our 88 results would take about 40 hr. of continuous work. However, the method was applied to three melts taken at random, but for which the agreement with the best-fit log k/log ΣCaO line was reasonably good. It was felt that the agreement in these three cases did not justify further work, but the results are given below:

Melt No.	Actual P Content, wt.-%.	P Content Predicted by Schenck and Riess' Method.
*C*3	0·076	0·034
*E*4	0·027	0·018
*P*3	0·020	0·017

It is doubtful whether Schenck and Riess' method could be used for the practical control of slag composition in industry, owing to the time taken for each determination. The present method has the advantage that if it is valid under industrial conditions it will be possible to draw large-scale charts, similar to Figs. 35–38, which may be readily used by the steelmelter during the refining period.

Slag Constitution.

It has already been mentioned that the linear relationship between log k and log ΣCaO is essentially empirical, yet it is not possible to obtain a more fundamentally sound relationship without a knowledge of the slag constitution in the liquid state. In the absence of a satisfactory technique for obtaining this information by direct methods, more than 50 of the slags have been examined in the solid state, using X-ray and petrographic methods. No attempt was made to carry out an exhaustive investigation of the slag constituents from a mineralogical point of view, because of the tedious and difficult nature of the problem. Water-quenched slags were originally used for the petrographic examination, but were found to be too fine-grained for satisfactory results to be obtained. Most of this work was therefore carried out on slags which had been allowed to cool in the experimental furnace with the top open. For a number of melts both quenched and furnace-cooled slags were examined by X-rays and no significant difference could be detected. For the rest of the X-ray work, therefore, the quenched slags were employed, and, as there was no real divergence between the results of the X-ray and petrographic examinations, it may be assumed that the rate of cooling in the furnace is sufficiently fast to suppress further modification in the solid state.

Thin sections of a number of representative furnace-cooled slags were examined petrographically, and three distinct phases were recognized. These consisted of:

(i) Anisotropic primary crystals, sometimes dendritic in form, which were colourless in unpolarized transmitted light and gave weak polarization colours under crossed nicols. Double refraction was correspondingly low, probably of the order of 0·003–0·005.

(ii) A yellowish-brown constituent which surrounded the primary crystals. Under crossed nicols this phase exhibited bright yellow to yellowish-red polarization colours and the double refraction was of the order of 0·09. The refractive index was also much higher for this phase than for the primary crystals referred to above.

(iii) An opaque isotropic constituent which occurred as interstitial matter, the colour varying from dark brown to black.

These three different phases can be recognized in Figs. 9 and 10, which were obtained from typical slags in transmitted light. Fig. 11 shows the appearance of the field given in Fig. 9 when viewed under crossed nicols. In this figure the bright clusters correspond to the yellowish-brown constituent (ii) and the grey areas to the anisotropic primary crystals (i).

X-ray examination by the powder method using Co radiation also revealed the presence of three distinct phases, and on the basis of this and the petrographic work, the phases were identified as (i) a silico-phosphate phase, (ii) dicalcium ferrite with possibly brownmillerite in solid solution, and (iii) a solid solution of the three oxides, FeO, MgO, and MnO. Since the elucidation of the silico-phosphate phase involves considerable discussion, it will be convenient to leave this until the evidence for the other two phases has been described.

Ferrite–Aluminate Phase.

X-Ray Data.—The structures of dicalcium ferrite, of the ternary compound $4CaO.Al_2O_3.Fe_2O_3$, and of the continuous series of solid solutions which are formed between them are all very similar, and it is difficult to distinguish between them in patterns obtained from basic slags. The common structure, confirmed by comparison with a standard of dicalcium ferrite, was identified in all the slags examined. No evidence of a separate calcium aluminate or alumina phase was obtained even in the high-alumina series, where there was more alumina present than was necessary for the formation of the ternary compound $4CaO.Al_2O_3.Fe_2O_3$. It must be borne in mind, however, that small percentages, depending upon the crystal symmetry, can be present and not detected by X-ray methods.

Petrographic Data.—Owing to the similarity of the crystal structures of dicalcium ferrite and $4CaO.Al_2O_3.Fe_2O_3$, the optical properties are also very similar, so that the two compounds are likely to be confused in microscopic examination. By preparing standards of $2CaO.Fe_2O_3$ and of $4CaO.Al_2O_3.Fe_2O_3$, it was possible to show that the dicalcium ferrite was bright red, whereas the ternary compound was yellowish-brown. This difference in colour was clearly visible under crossed nicols. All slags with the molecular ratio Al_2O_3/Fe_2O_3 less than unity contained the ferrite–aluminate phase with a colour intermediate between that of the dicalcium ferrite and the ternary compound. It is reasonable to suppose that this corresponded to a solid solution of the two compounds. No evidence was obtained for the existence of a calcium aluminate in those slags for which the molecular ratio Al_2O_3/Fe_2O_3 was greater than unity, but the complex intergrowth of the different phases makes the detection of small amounts extremely difficult.

General.—As far as it goes, the X-ray and petrographic evidence is in agreement that the yellowish-brown constituent observed to surround the primary crystals probably consists of a solid solution between dicalcium ferrite and brownmillerite.

Oxide Phase.

X-Ray Data.—The four oxides MgO, FeO, MnO, and CaO all possess cubic structures of the rock-salt type with parameters 4·20, 4·27–4·30, 4·43, and 4·80 Å. respectively. The cubic pattern which was given by all the slags examined did not agree with any of these structures, but corresponded to intermediate parameters. Thus, the values of the side of unit cube *a* calculated from the 220 diffractions for a number of slags are given in Table III.

It will be seen that in the series *C*, *D*, and *E*, for which the MnO content was less than 1·5%, the parameter is intermediate between those for MgO and FeO, and the oxide phase may therefore be regarded as mainly a solid solution of these two oxides. For the two high-MnO series, containing 6 and 10% of MnO respectively, the parameter is greater than that for FeO, although still less than that of MnO. It seems likely that in this case the oxide phase is a solid solution of MgO, FeO, and MnO.

No evidence of free lime was observed in any of the slags. It is possible, as Rait and Goldschmidt [18] have suggested, that small quantities may go into solution in the oxide phase without the formation of a separate structure, particularly in the high-MnO slags. It should also be borne in mind that all the slags examined by X-rays have been very rapidly cooled from the molten state, and it is possible that the slags have, in fact, been quenched from above the immiscibility gap observed by Oelsen and Maetz.[7] Another possibility is that the free lime present in the molten state enters into combination on solidification and is observed in the solid slag as dicalcium ferrite. An important feature of our work, and one which may account for some of the differences between it and corresponding work carried out on industrial slags, is that our slags were completely prefused at a high temperature and no lime was added during the course of a melt. There was therefore no possibility of undissolved lime persisting to the end of the melt.

TABLE III.—*Values of the Side of Unit Cube for the Oxide Phase in a Number of Slags.*

Slag No.	Intensity of 220 Line.	Side of Unit Cube (*a*), Å.
*C*3	Strong.	4·243
*C*6	Strong.	4·242
*C*7	Strong.	4·242
*D*4	Strong.	4·267
*D*6	Medium.	4·242
*E*3	Strong.	4·267
*E*4	Medium.	4·289
*E*6	Weak.	4·292
*MnX*4	Strong.	4·298
*MnX*6	Strong.	4·298
*MnX*8	Strong.	4·326
*MnY*5	Strong.	4·337
*Al*2	Strong.	4·242

Petrographic Data.—No attempt was made to carry out a detailed petrographic examination of this phase, but it was easily recognized as a very dark, isotropic material of high refractive index. In certain specimens evidence was obtained that the phase contained MgO in solid solution. Thus, in Fig. 12 the large crystals consist of MgO picked up from the hearth and show cleavage lines at right angles in accordance with the isotropic nature of this material. Close

examination reveals that these crystals are in the process of dissolving in the oxide phase, and in the boundary regions there is a gradual change in appearance from the transparent MgO to the very dark oxide phase. Magnesia crystals were not generally observed in the slags, and in this particular case they were almost certainly introduced at the moment of sampling.

General.—The evidence confirms the view that the dark interstitial material observed in these basic slags consists essentially of solid solutions of FeO, MnO, and MgO. No direct evidence was obtained for the presence of CaO in this solid solution, nor was free lime detected by either X-ray or petrographic methods.

Silico-Phosphate Phase.

It is generally agreed that $3CaO.P_2O_5$ and $2CaO.SiO_2$ form a quasi-binary system, but there is still divergence of opinion as to the extent of the phase fields involved. Among the constituents which have been isolated may be mentioned silico-carnotite ($5CaO.P_2O_5.SiO_2$) and nagelschmidtite ($7CaO.P_2O_5.2SiO_2$), both of which have been observed in basic slags. According to Trömel,[8] there are three phase-fields between dicalcium silicate and silico-carnotite. They are (i) α-$2CaO.SiO_2$, which is capable of dissolving up to 2 mol.-% of $3CaO.P_2O_5$, (ii) the K phase covering the range 4·5–12 mol.-% of $3CaO.P_2O_5$, and (iii) the R phase, which contains from 17 to 57 mol.-% of $3CaO.P_2O_5$. Trömel considered that the silico-carnotite was formed in the solid state at about 1300° C. as a result of a peritectoid reaction between the R and α-$3CaO.P_2O_5$ phases. The diagram suggested by Barrett and McCaughey [20] differs from that of Trömel chiefly in the extent of the homogeneity ranges of the different phases and in the absence of the K phase. Moreover, silico-carnotite is considered to be stable at all temperatures below the solidus, within the range 51–65 mol.-% of $3CaO.P_2O_5$.

Bredig,[19] on the other hand, has proposed an entirely new diagram, according to which compositions from 0 to 50 mol.-% of $3CaO.P_2O_5$ form solid solutions at high temperatures, having the common structure of the α-hexagonal form. This structure is most stable in the case of nagelschmidtite, in which it is readily retained in a metastable form to room temperature. According to Bredig, β-$2CaO.SiO_2$ and silico-carnotite are formed only as a result of transformation in the solid state, the former passing through an α' field before changing to the β form at a lower temperature. Bredig stated that the intermediate α' phase gave an X-ray pattern which was similar to that yielded by the K phase reported by Trömel. Greene [21] has shown that the α-hexagonal structure is possessed at high temperatures by solid solutions of dicalcium silicate with Na_2O and Fe_2O_3 or Al_2O_3, but he was unable to confirm the occurrence of the intermediate α' form. It may be mentioned, however, that Rait and Goldschmidt have recently reported the occurrence in some oxidizing slags of a high-temperature intermediate phase, which they designated α'.

Because of the uncertain nature of the silico-phosphate constituent, it was considered desirable to prepare synthetic standards containing various proportions of $2CaO.SiO_2$ and $3CaO.P_2O_5$. The

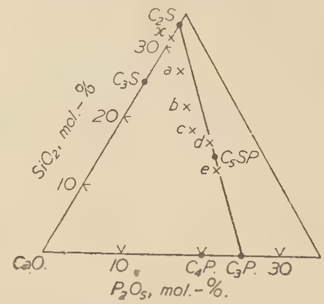


Fig. 39.—Compositions of Synthetic Standards.

appropriate quantities of calcined pure precipitated chalk, pure precipitated silica, and of pure tribasic calcium phosphate were carefully mixed in a small ball-mill and then fused in an electric arc in the manner which has already been described. Since the fused material came into contact only with the powder from which it was made, there was no danger of contamination. As soon as an adequate amount of powder had been fused, the arc was switched off and the fused mass was rapidly quenched in cold water. The melts were then sampled and suitable portions taken for chemical analysis. The six melts which were prepared contained nominally 0, 10, 20, 30, 40, and 50 mol.-% respectively of $3CaO.P_2O_5$, and the actual chemical analyses are given in Table IV. The results have also been plotted on a ternary CaO–SiO_2–P_2O_5 diagram in Fig. 39, and it will be seen that the points lie very close to the tie-line between $2CaO.SiO_2$ and $3CaO.P_2O_5$, so that the standards may be regarded as representing the binary system $2CaO.SiO_2$–$3CaO.P_2O_5$. These

Table IV.—*Composition of Standards.*

Melt.	Analysis, wt.-%.			Analysis, mol.-%.		
	CaO.	SiO_2.	P_2O_5.	CaO.	SiO_2.	P_2O_5.
X	65·3	31·5	...	68·8	31·2	...
a	64·3	26·1	8·7	69·8	26·7	3·7
b	63·6	20·4	15·0	71·5	21·5	7·0
c	62·2	16·7	21·5	72·2	18·2	9·7
d	59·0	14·3	26·5	71·1	16·2	12·8
e	59·3	10·5	32·4	72·2	12·3	15·6

standards were examined by X-ray and petrographic methods, and compared with the silico-phosphate phase observed in the slags.

X-Ray Data.—The X-ray patterns of standards *b* and *c* in the water-quenched condition, and also after annealing at 1000° C. for 5 hr. followed by furnace cooling, corresponded to the α-hexagonal structure generally associated with nagelschmidtite. The observed spacings and those calculated for the structure assigned by Bredig [19] to nagelschmidtite (hexagonal, $a = 5{\cdot}36$ Å.; $c = 7{\cdot}08$ Å.) are given in Table V.

The patterns given by standard *e*, and to a lesser extent those of standard *d*, differed in the water-quenched and annealed conditions. To assist in the interpretation of these patterns, a standard corresponding to silico-carnotite, $5CaO.P_2O_5.SiO_2$,

TABLE V.—*X-Ray Results for Standards* b *and* c *Compared with Calculated Data for Nagelschmidtite.*

Nagelschmidtite.		Standard *b*.		Standard *c*.	
Diffraction.	Spacing, Å.	Spacing, Å.	Intensity.	Spacing, Å.	Intensity.
101	3·88	3·86	W.	3·87	W.
002	3·54	...	...	3·44	W.
...	...	2·94	W.	2·95	M.
102	2·81	2·80	S.	2·80	S.
110	2·68	2·66	S.	2·67	S.
200	2·33	...	...	2·29	W.
201	2·21	2·20	M.	2·20	W.
112	2·14	2·14	W.	...	...
202	1·94	1·94	S.	1·94	S.
004	1·77	...	...	...	...
120	1·76	...	...	1·74	W.
104	1·66	...	...	...	...
122	1·58	1·57	W.	1·57	W.
114	1·48	1·48	W.	1·48	W.
204	1·41	...	...	...	...
220	1·34	1·34	W.	1·34	W.

W. = weak, M. = medium, S. = strong.

was prepared and the X-ray pattern of the annealed material was taken. The observed spacings were found to agree with those of a hexagonal structure with parameters $a = 6{\cdot}85$ and $c = 7{\cdot}33$ Å. and fairly well with those reported by Nagelschmidt [22] for silico-carnotite. Spacings for nagelschmidtite, silico-carnotite, and the standards *d* and *e* are given in Table VI. The water-quenched standard *d* was entirely nagelschmidtite, but in the annealed state there was some evidence of the presence of silico-carnotite, the 112 and 120 diffractions appearing, whilst those lines which were common to nagelschmidtite and silico-carnotite were stronger in the pattern of the annealed sample. The diffractions were mainly those of nagelschmidtite, but the fact that silico-carnotite lines were obtained from the annealed material indicates the existence of a two-phase region.

In the water-quenched state, standard *e* consisted mainly of nagelschmidtite though mixed with rather more silico-carnotite than was observed in the annealed standard *d*. After annealing, the standard *e* was converted entirely to silico-carnotite. These results are in agreement with Bredig's diagram, and confirm the work of Klement and Streckenreiter,[23] who showed that silico-carnotite transformed to the α-hexagonal phase before melting. The presence of small amounts of silico-carnotite in the quenched standard *e* suggests that the rate of quenching was insufficient to suppress the transformation on cooling.

The spacings observed for standards *X* and *a*, in both water-quenched and annealed conditions,

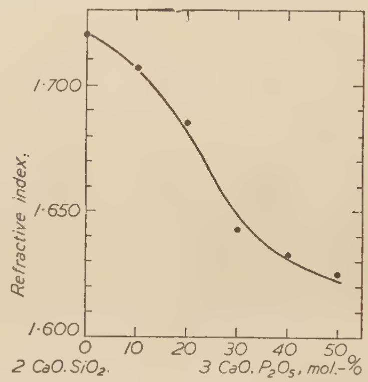


FIG. 40.—Effect of $3CaO.P_2O_5$ upon the Refractive Index of $2CaO.SiO_2$ Solid Solutions.

agreed well with those reported by Phemister [24] for β-dicalcium silicate. This is illustrated in Table VII.

The patterns from the quenched standards were the same as those from the corresponding annealed material, except that weak lines occurred in *X* at 2·84 Å. and in *a* at 3·12, 2·96, and 2·84 Å. An exact explanation of these lines cannot be given, but it seems probable that they are due to the retention of small quantities of a high-temperature form.

Petrographic Data.—Visual examination of thin sections of the water-quenched standards under the microscope showed that a single phase was present in each case except standard *e*, and that the birefringence decreased with increasing $3CaO.P_2O_5$ content. No attempt was made to determine the optical properties in detail, but Fig. 13, obtained from standard *c*, corresponds to a single phase. In Figs. 14 and 15, obtained from standard *e* in the powder and thin-section form, respectively, most of the crystals have the appearance of twinning, which suggests that water-quenching is not sufficiently drastic to suppress transformation in the solid state, so that some of the low-temperature form is produced along

TABLE VI.—*X-Ray Results for Standards* d *and* e.

Nagelschmidtite.		Silico-Carnotite.		Standard *d*.				Standard *e*.			
				Water-Quenched.		Annealed.		Water-Quenched.		Annealed.	
Diffraction.	Spacing, Å.	Diffraction.	Spacing, Å.	Spacing, Å.	Intensity.	Spacing, Å.	Intensity.	Spacing, Å.	Intensity.	Spacing, Å.	Intensity.
101	3·88	...	...	3·84	M.	3·84	M.	3·86	M.	...	...
002	3·54	...	...	3·41	M.	3·40	M.	...	...	...	...
...	...	...	...	...	...	...	...	3·33	M.	...	...
...	...	102	3·22	...	...	...	...	3·19	W.	3·24	S.
...	...	...	...	...	...	...	...	...	...	3·05	M.
...	...	200	2·97	2·92	M.	2·94	S.	...	...	2·98	M.
102	2·81	201	2·77	2·80	S.	2·80	S.	...	...	...	...
110	2·68	...	...	2·64	S.	2·64	M.	...	...	...	...
...	...	112	2·56	...	...	2·56	W.	2·58	S.	2·57	S.
200	2·33	202	2·35	2·30	W.	2·30	W.	2·36	W.	2·36	S.
...	...	120	2·25	...	...	2·24	W.	2·27	S.	2·25	S.
201	2·21	...	...	2·18	W.	2·19	W.	...	...	...	...
112	2·14	121	2·16	...	...	2·14	W.	2·15	W.	2·15	M.
...	...	300	1·98	...	...	...	...	...	...	1·98	M.
202	1·94	203	1·94	1·93	S.	1·93	M.	1·93	W.	1·94	M.
...	...	004	1·92	...	...	...	...	...	...	1·91	M.
...	...	104	1·83	...	...	...	...	1·80	M.	1·80	S.
004	1·77	302	1·76	1·78	M.	1·79	W.	...	...	...	...
120	1·76					1·74	M.				
104	1·66	114	1·68	...	...	...	...	1·67	W.	1·67	S.
122	1·57	...	...	1·57	M.	1·57	W.	...	...	...	...
114	1·48	105	1·49	1·49	W.	1·49	W.	1·49	W.	1·49	M.
204	1·41	...	...	1·43	W.	...	...	...	...	...	...
220	1·34	...	...	1·33	W.	1·34	W.	1·33	W.	...	...

W. = weak, M. = medium, S. = strong.

the cleavage planes to give a characteristic lamellar structure. A later stage in the process was observed in the annealed specimen, which

TABLE VII.—*X-Ray Results for Standards* X *and* a *Compared with Data for* β-$2CaO.SiO_2$.

β-$2CaO.SiO_2$ (Phemister's data).		Annealed Standard *X*.		Annealed Standard *a*.	
Spacing, Å.	Intensity.	Spacing, Å.	Intensity.	Spacing, Å.	Intensity.
3·03	W.	3·02	W.	3·01	W.
2·76	S.	2·76	S.	2·74	S.
2·69	S.	2·69	S.	2·69	S.
2·66	W.	...	...	...	...
2·58	V.W.	2·58	M.	...	...
2·45	W.	2·38	W.	2·43	W.
2·25	W.	2·26	W.	...	...
2·18	M.	2·17	S.	2·20	S.
2·02	W.	...	...	2·04	W.
1·98	M.	1·97	M.	...	...
1·89	W.	1·88	W.	1·92	S.
1·80	W.	1·79	W.	...	...
1·70	V.W.	...	...	...	...
1·63	M.W.	1·62	M.	...	...
1·61	M.W.	1·60	W.	1·59	W.
1·57	V.W.	...	...	1·56	M.
1·55	V.W.	...	...	...	...
1·52	V.W.	...	...	...	...
1·48	V.W.	1·47	W.	1·44	W.
1·39	V.W.	...	...	...	...
1·37	V.W.	1·37	W.	1·35	W.

V.W. = very weak, W. = weak, M.W. = medium weak, M. = medium, S. = strong.

had the appearance shown in Fig. 16, in keeping with the complete disintegration of the high-temperature form into crystallites of silico-carnotite.

With a view to identifying the silico-phosphate constituent observed in the slags, the average refractive indices of the standards were determined by the immersion method. The liquids employed for this purpose were methylene iodide, α-bromonaphthalene, and benzyl benzoate, the refractive indices of which were known. In order to estimate the refractive index of a material falling between these limits, it was assumed that the refractive index of a mixture of two liquids with volumes and refractive indices V_1, V_2, and n_1, n_2 respectively, was given by :

$$n_1V_1 + n_2V_2 = n(V_1 + V_2).$$

Although there is no sound theoretical basis for this assumption, it is known that the errors involved are small, provided that the liquids do not possess widely different densities.

The results obtained for the standard melts are plotted in Fig. 40, and it will be seen that the refractive index decreases with increasing content of $3CaO.P_2O_5$. As will be explained later, it was found possible to estimate the composition of the silico-phosphate constituent occurring in the slags, by making use of the relationship shown in Fig. 40.

General.—The results of both X-ray and petrographic examinations point to the existence of an α-hexagonal silico-phosphate at high temperatures, at least within the range 20–50 mol.-% of $3CaO.P_2O_5$. The lower limit may be less than 20 mol.-%, but the X-ray results show that β-$2CaO.SiO_2$ is the only constituent in the standards containing 0 and 10 mol.-%, respectively, of $3CaO.P_2O_5$. Thus the nagelschmidtite structure is possessed by such a wide range of solid solutions at high temperatures that it would be misleading to attempt to assign any definite chemical formula to this phase, and it would seem preferable to refer to it as the α-hexagonal silico-phosphate phase. X-ray examination shows that at a lower temperature the α-hexagonal phase containing 50 mol.-% of $3CaO.P_2O_5$ transforms to silico-carnotite, and the petrographic evidence is in accord with this view. In general, the results reported here for the silico-phosphate phase are in agreement with Bredig's diagram.

The Silico-Phosphate Phase Observed in the Slags.

X-Ray Data.—Slags of series *P*, with molecular ratio $(P_2O_5)/(SiO_2) + (P_2O_5)$ between 0·1 and 0·2, gave X-ray patterns containing lines due to the β-$2CaO.SiO_2$ solid solution. The spacings observed for the three most prominent diffractions from slag P_2, typical of the series, are given in Table VIII. and compared with those for β-$2CaO.SiO_2$, given by Phemister, and those observed for the standard *a*. No evidence for the existence of another silicate or silico-phosphate phase was obtained.

TABLE VIII.—*X-Ray Data for the Silico-Phosphate Phase in a Slag of Series* P.

Slag P_2.		Standard *a*.		β-$2CaO.SiO_2$.	
Spacing, Å.	Intensity.	Spacing, Å.	Intensity.	Spacing, Å.	Intensity.
2·68	M.	2·69	S.	2·69	S.
2·40	W.	2·43	W.	2·45	W.
2·19	S.	2·20	S.	2·18	M.

W. = weak, M. = medium, S. = strong.

Representative slags from each series of melts, except *A*, were examined by X-rays, and altogether patterns of more than half the total number of slags were obtained. In all cases, except the *P* series already considered, the only silicate or silico-phosphate phase observed was that of the α-hexagonal silico-phosphate form. It was difficult to distinguish some of the lines from those of dicalcium ferrite and the oxide phase, but the 102 and 110 diffractions, with spacings 2·80 and 2·66 Å. respectively, were clearly visible and in most cases the intensity was strong.

The occurrence of the α-hexagonal phase in the slags from the *C* series of melts calls for special comment, because the lime is insufficient for the formation of a silico-phosphate containing all the silica and P_2O_5. In a classification of industrial slags according to the basicity index $CaO/(SiO_2 + P_2O_5)$, Mason [25] stated that he observed merwinite when this ratio was between 1·4 and 1·6, and dicalcium silicate when the ratio was between 1·6 and 2·4. On this basis the dicalcium silicate pattern would be expected from series *P*, whilst merwinite should occur in the slags of series *C*, although it must be borne in mind that all the slags examined by Mason were low in P_2O_5. The X-ray pattern of merwinite is very similar to that of β-$2CaO.SiO_2$, according to Phemister, and no indication of its presence was obtained in the X-ray patterns of the *C* series. It is known that when there is a deficiency of lime, MgO may replace CaO in β-$2CaO.SiO_2$, molecule by molecule, to give merwinite, $3CaO.MgO.SiO_2$, and monticellite, $CaO.MgO.SiO_2$, respectively, and that all three compounds possess very similar crystal structures with almost identical optical properties, except that merwinite shows polysynthetic twinning in thin sections.

It seems likely that in the presence of P_2O_5 these compounds may be able to form series of solid solutions with $3CaO.P_2O_5$, and, indeed, Schneiderhöhn [26] claimed to have detected such substituted silico-phosphates, although he did not give their detailed properties. If such substituted silico-phosphates exist, the high-temperature form may be expected to possess the α-hexagonal structure as suggested, more generally, by Bredig.[27] To throw more light upon this point, three standards were prepared with the chemical analyses shown in Table IX.

The three standards *P*, *Q*, and *R* correspond approximately to the compounds

$$3CaO.MgO.2SiO_2.3CaO.P_2O_5,$$
$$2(3CaO.MgO.2SiO_2).3CaO.P_2O_5,$$

and $2(CaO.MgO.SiO_2).3CaO.P_2O_5$, respectively, and in each case gave an X-ray pattern corresponding to a single phase possessing the structure of the α-hexagonal silico-phosphate. The substitution of MgO for CaO appears to result in the spacings being slightly reduced, as indicated in Table X., where the observed spacings are compared with those for $2(2CaO.SiO_2).3CaO.P_2O_5$.

The results given in Table X. support the view that MgO may replace CaO in the α-hexagonal silico-phosphate with but slight changes in lattice parameters. The reduction actually observed is in keeping with the fact that CaO occupies more space than MgO, the size of the respective unit cells being 4·80 and 4·20 Å. It is not possible

TABLE IX.—*Chemical Data for Standards* P, Q, *and* R.

Standard.	Constituent.	Wt.-%.	Mol. Ratio.
P	CaO	52·6	5·8
	SiO_2	17·6	1·8
	P_2O_5	23·1	1·0
	MgO	6·7	1·0
Q	CaO	52·1	8·4
	SiO_2	23·6	3·53
	P_2O_5	15·8	1·0
	MgO	7·76	1·74
R	CaO	45·1	4·8
	SiO_2	18·0	1·8
	P_2O_5	23·9	1·0
	MgO	12·3	1·8

to say whether a substituted silico-phosphate occurs in series *C* merely on the basis of spacing in powdered form, and the refractive index of the silico-phosphate phase was determined approximately by the immersion method. The curve relating the refractive index with composition, based on the examination of synthetic standards, was used, but no attempt was made to match the refractive index of the slag by mixing the appropriate liquids in exact proportions. In this manner considerable time was saved, yet the results were sufficiently accurate to make identification of the silico-phosphate phase possible on the basis of the P_2O_5/SiO_2 ratio, as indicated in Table XI.

It is reasonable to suppose that the agreement between the results given in columns 3 and 4 of Table XI. would have been much closer had the refractive index of the slag been more accurately matched in all cases, but the agreement is sufficiently good to justify the conclusion that all

TABLE X.—*Comparison of X-Ray Data for Nagelschmidtite and Standards* P, Q, *and* R.

Nagelschmidtite (calculated data).		Standard *P*.		Standard *Q*.		Standard *R*.	
Diffraction, *hkl.*	Spacing, Å.	Spacing, Å.	Intensity.	Spacing, Å.	Intensity.	Spacing, Å.	Intensity.
101	3·88	3·82	W.	3·85	M.	3·84	M.
002	3·54	3·43	W.	3·42	M.	3·41	M.
102	2·81	2·77	S.	2·80	S.	2·80	S.
110	2·68	2·64	S.	2·64	S.	2·63	S.
200	2·33	2·29	W.	2·30	W.	2·28	M.
201	2·21	2·18	M.	2·18	W.	2·17	M.
112	2·14	2·08	W.	2·09	W.	2·09	W.
202	1·94	1·92	S.	1·92	S.	1·92	S.
004	1·77	...	...	1·77	W.	...	...
120	1·76	...	...	1·73	M.	1·73	M.
104	1·66	...	...	...	...	1·67	W.
122	1·58	1·56	W.	1·56	W.	1·55	W.
114	1·48	1·48	W.	1·49	M.	1·48	M.
204	1·41	...	...	...	...	...	...
220	1·34	1·33	W.	1·33	W.	1·32	W.

W. = weak, M. = medium, S. = strong.

determinations. On the other hand, the slags of series *P* have approximately the same P_2O_5/SiO_2 ratio as those of series *C*, and the conclusion may be drawn that partial substitution of MgO for CaO in low-P_2O_5 silico-phosphates causes the α-hexagonal form to be retained on quenching instead of the β-2CaO.SiO_2. If Bredig's diagram be accepted, this means that the α-hexagonal form is stabilized to a lower temperature, in this range of compositions, by the substitution of MgO for CaO. The non-occurrence of the merwinite indicated by Mason's classification is probably due to the rapid quenching to which our slags were subjected.

Petrographic Data.—As very little information regarding the silico-phosphate phase was obtained from the preliminary petrographic examination of thin sections of eight of the slags, representative slags of most of the series of melts were examined

the silica and all the P_2O_5 is contained in a single silico-phosphate phase.

Melts of series *A* and *C* were carried out at an early stage, and owing to an oversight the corresponding slags were not available for this work.

Standards *P*, *Q*, and *R* were examined in powder form and found to consist of a single phase in each case. The birefringence appeared to diminish with increasing magnesia content.

General.—The results obtained in the examination of slags and standards for the silico-phosphate phase lead to the following conclusions :

(1) All the SiO_2 and all the P_2O_5 contained in the slag is in the form of a silico-phosphate.

(2) If sufficient lime is present, a lime silico-phosphate, 2CaO.SiO_2.x(3CaO.P_2O_5), is formed.

(3) When there is a deficiency of lime, MgO

may replace some of the CaO in the silico-phosphate.

(4) The silico-phosphate generally observed in quenched slags possesses the α-hexagonal structure and optical properties associated with nagelschmidtite, but is to be regarded as an extensive range of solid solutions rather than as a compound.

TABLE XI.—*Identification of the Silico-Phosphate Phase from its Refractive Index.*

Slag No.	Refractive Index of the Silico-Phosphate.	$3CaO.P_2O_5$, % (deduced from Refractive Index, using Fig. 40).	$3CaO.P_2O_5$ in Solid Solution (from chemical analysis), %.
*E*2	Close to 1·658	Close to 26·5	27·1
*D*1	,,	,,	27·8
*D*2	,,	,,	25·0
*D*3	,,	,,	24·0
*D*4	,,	,,	26·6
*D*8	1·677	21·0	21·4
*D*13	<1·658	>26·5	32·5
*Mn*6	Close to 1·658	Close to 26·5	29·6
*Mn*7	,,	,,	29·6
*Mn*10	1·658	26·5	27·6
*Mn*11	1·674	22·0	22·8
*Mn*12	Just <1·658	Just >26·5	29·4
*Mn*13	,,	,,	30·6
*MnX*1	,,	,,	32·2
*MnX*2	,,	,,	29·3
*MnX*3	,,	,,	30·8
*MnX*4	,,	,,	30·6
*MnX*7	<1·658	>26·5	31·2
*MnX*8	Just <1·658	Just >26·5	29·1
*MnY*1	<1·658	>26·5	35·2
*MnY*2	,,	,,	31·2
*MnY*3	,,	,,	32·2
*MnY*4	,,	,,	31·8
*MnY*6	1·658	26·5	27·6
*MnY*7	1·658	26·5	28·0
*MnY*11	1·658	26·5	28·6
*P*1	<1·699	>13·5	18·1
*P*2	1·699	13·5	15·2
*P*3	Just <1·699	Just >13·5	15·5
*P*4	,,	,,	15·4
*P*5	,,	,,	16·0
*P*6	1·699	13·5	15·2
*P*8	1·699	13·5	14·5
*Al*1	1·658–1·668	23·5–26·5	26·0
*Al*2	,,	,,	25·6
*Al*3	1·658	26·5	26·5
*Al*4	1·658–1·668	23·5–26·5	25·5
*Al*5	,,	,,	25·6
*Al*6	,,	,,	25·3
*Al*7	1·668	23·5	25·0
*Al*8	,,	,,	25·1
*Al*9	1·674	22·0	22·7

(5) When the P_2O_5 content of the slag is low, the silico-phosphate occurs as a solid solution of $3CaO.P_2O_5$ in β-$2CaO.SiO_2$, and it is possible that this is formed as a result of transformation, during cooling, of an α-hexagonal form as suggested by Bredig.

(6) In the standards of molecular ratio $P_2O_5/SiO_2 = 1$, the silico-phosphate retained by quenching consists of a mixture of the α-hexagonal form with silico-carnotite. In annealed samples only silico-carnotite occurs, thus showing that it should be regarded as a product of the transformation on cooling of the α-hexagonal form. No evidence of silico-carnotite was obtained from any of the slags examined, but the P_2O_5/SiO_2 ratio was in all cases less than unity.

Some of these conclusions may appear at first sight to be contrary to current opinion as to the constitution of basic slags, but it must be remembered that our slags were cooled fairly rapidly and that no attempt was made to realize equilibrium conditions during cooling.

Statistical Treatment of the Analytical Results in the Light of the Probable Slag Constitution at High Temperatures.

It has already been shown that a linear relationship exists between log k for the phosphorus reaction and log ΣCaO in the slag, but it was pointed out that this relationship was only empirical. It might be expected that a relationship more in accord with physico-chemical principles could be found if free lime were used in place of the total lime, but in order to do this it is necessary to make certain assumptions as to the slag constitution in the molten state. Examination of the slags reported in the previous section showed that a silico-phosphate was formed containing all the SiO_2 in the slag in the form of $2CaO.SiO_2$, and all the P_2O_5 as $3CaO.P_2O_5$, and in view of the high melting points of such silico-phosphates it may be assumed that they are stable at steelmaking temperatures. Evidence was obtained that some of the lime was combined with Fe_2O_3 in the form of $2CaO.Fe_2O_3$, but it was not possible to decide whether or not alumina was combined with CaO in any form. In view of the low melting point of the $2CaO.Fe_2O_3$ and the general uncertainty as to the amount of lime used up in combination with the Fe_2O_3 and Al_2O_3 in the liquid slags, it was decided to treat the results statistically on a molecular per cent. basis, making various assumptions in turn. In all cases except series *C* the formation of $2CaO.SiO_2$ and of $3CaO.P_2O_5$ was assumed, and various degrees of association of CaO with Fe_2O_3 and Al_2O_3 were considered. Examination of the slags of series *C* had shown that the partial substitution of MgO for CaO was probable, and that unless such substitution occurred there would be no free lime in the slag. For series *C*, therefore, it was assumed that in the silicate one molecule of CaO in four was replaced by MgO, which is equivalent to the formation of merwinite, and it is interesting to note that this caused the results for series *C* to fall in line with those of other series. The various assumptions made

concerning the amount of CaO necessary for the Fe_2O_3 and Al_2O_3 are given in Table XII. together with the gradients of best-fit straight lines and the corresponding correlation coefficients.

The assumption that $3CaO.P_2O_5$ is formed is equivalent to assuming that the equation for the complete phosphorus reaction is :

$$2P + 5FeO + 3CaO \rightleftharpoons 3CaO.P_2O_5 + 5Fe \quad . \quad (12)$$

and therefore, plotting log k for the equation :

$$2P + 5FeO \rightleftharpoons P_2O_5 + 5Fe \quad . \quad . \quad . \quad (1)$$

against log (free lime) should result in a straight line of gradient 3. From this point of view, the assumption that no lime is used up by Al_2O_3 and that CaO is associated with Fe_2O_3 to the extent of $0{\cdot}75CaO.Fe_2O_3$ gives the most satisfactory figure of 3·07 for the gradient of the best-fit straight line. Whilst the correlation coefficient for this assumption is slightly lower than the highest obtained, it is still significant. The results for series *A* were not used for this statistical treatment, because no evidence had been obtained with regard to the constitution of slags of this series, so that only 73 results were available, which means that the correlation is significant if $r > 0{\cdot}3$.

TABLE XII.—*Assumptions of CaO Necessary for Fe_2O_3 and Al_2O_3.*

Combination Assumed to Occur in Molten Slags.	Gradient.	Correlation Coefficient, *r*.
$2CaO.Fe_2O_3$	2·11	0·71
$CaO.Fe_2O_3$	2·61	0·73
$CaO.Fe_2O_3$ and $CaO.Al_2O_3$.	1·94	0·65
$0{\cdot}5CaO.Fe_2O_3$ and $CaO.Al_2O_3$.	2·27	0·62
$0{\cdot}5CaO.Fe_2O_3$ and $0{\cdot}5CaO.Al_2O_3$	2·50	0·74
$0{\cdot}5CaO.Fe_2O_3$	3·40	0·74
$0{\cdot}75\ CaO.Fe_2O_3$	3·07	0·72
Ignoring Fe_2O_3 and Al_2O_3 .	3·64	0·68

The correlation coefficient is smaller, and the scatter of the points correspondingly greater, when free lime is used instead of total lime, and this is to be attributed to the fact that analytical errors of a given magnitude are greater in proportion when free lime is used.

It is not claimed that the data given in Table XII. necessarily enable a true picture of the $CaO\text{–}Fe_2O_3\text{–}Al_2O_3$ relationship in molten slags to be obtained. A line of similar slope and better correlation coefficient might result if some other assumption with regard to the association of CaO with Fe_2O_3 and Al_2O_3 were made, whilst the results would be different if some dissociation of the $2CaO.SiO_2$ were assumed. It is clear that a really satisfactory quantitative treatment of the phosphorus reaction cannot be given without further knowledge of the relationships existing between slag constituents at steelmaking temperatures, particularly between CaO, Fe_2O_3, and Al_2O_3.

Of the assumptions made in deriving the results given in Table XII., that in which the alumina was ignored and each molecule of Fe_2O_3 required 0·75 molecules of CaO gave the slope nearest to the theoretical value of 3, and may be regarded as the most probable, subject to the limitations already mentioned. The numerical values for this case are given in Table XIII. and plotted in Fig. 41, together with the regression lines and the line which bisects the angle between them—which has been referred to above as the best-fit straight line. Fig. 41 may be used to calculate the most probable value of the equilibrium constant :

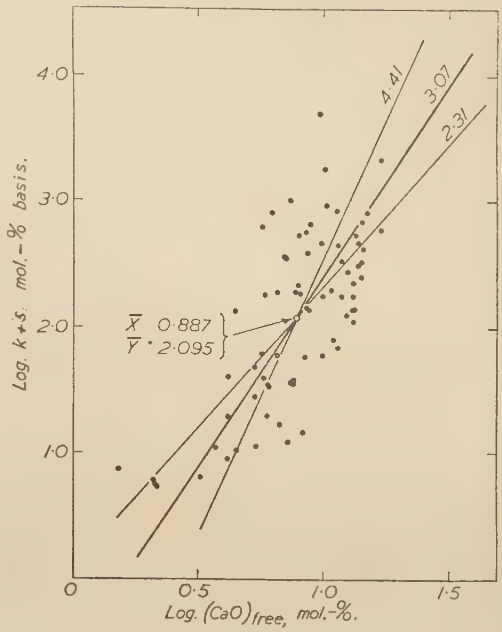


FIG. 41.—Relationship between log $k + 5$ and log (free CaO) on a molecular per cent basis, assuming $3CaO.P_2O_5$, $2CaO.SiO_2$, $0{\cdot}75CaO.Fe_2O_3$ and $r = 0{\cdot}724$.

$$K = \frac{(P_2O_5)}{[P]^2(FeO)^5(CaO)^3}$$

corresponding to equation (12). This constant will be equal to the constant :

$$k = \frac{(P_2O_5)}{[P]^2(FeO)^5}$$

of Fig. 41 when log (free lime) is zero. On this basis the most probable value of K, subject to the assumptions which have been made regarding Fe_2O_3 and Al_2O_3, is $2{\cdot}72 \times 10^{-6}$ at 1585° C.

CONCLUSIONS.

The work described in this paper appears to justify the following conclusions :

(1) The experimental technique which has been

TABLE XIII.—*Statistical Treatment of Results, Assuming Formation of* $3CaO.P_2O_5$, $2CaO.SiO_2$, *and* $0{\cdot}75CaO.Fe_2O_3$.

Melt No.	X = log (CaO) free.	Y = log k + 5.	Melt No.	X.	Y.
*C*1	0·328	0·728	*MnX*1	0·647	1·018
*C*2	0·566	1·034	*MnX*2	0·747	1·789
*C*3	0·755	1·595	*MnX*3	0·759	2·251
*C*4	0·893	2·326	*MnX*4	0·617	1·270
*C*5	0·858	3·014	*MnX*5	0·639	2·129
*C*6	0·897	2·731	*MnX*7	0·751	2·777
*C*7	0·936	2·136	*MnX*8	0·845	2·539
*C*8	0·986	2·674	*MnY*1	0·179	0·875
*C*9	1·045	2·928	*MnY*2	0·608	0·940
*C*10	0·504	0·805	*MnY*3	0·616	1·594
*C*11	0·318	0·778	*MnY*4	0·719	1·674
*D*1	0·873	1·552	*MnY*5	0·807	2·265
*D*2	0·776	1·526	*MnY*6	0·819	1·215
*D*3	0·903	2·273	*MnY*7	0·851	1·085
*D*4	0·866	1·554	*MnY*10	0·772	1·285
*D*5	1·090	2·388	*MnY*11	0·919	1·766
*D*6	1·146	2·838	*MnY*12	0·883	2·280
*D*7	1·225	3·338	*P*1	0·914	1·149
*D*8	1·170	2·916	*P*2	1·053	1·842
*D*9	0·787	2·904	*P*3	1·121	2·732
*D*11	0·980	3·708	*P*4	1·134	2·499
*D*12	0·997	3·252	*P*5	1·025	2·295
*D*13	0·324	0·742	*P*6	1·111	2·234
*E*1	0·943	1·817	*P*7	1·111	2·137
*E*2	0·992	2·242	*P*8	1·220	2·778
*E*3	0·724	1·047	*P*9	1·111	2·049
*E*4	0·928	2·593	*Al*1	1·033	1·703
*E*5	1·086	3·092	*Al*2	1·111	2·151
*E*6	1·146	3·391	*Al*3	1·149	2·627
*E*7	0·885	1·579	*Al*4	1·137	2·524
*Mn*4	0·725	1·452	*Al*5	1·107	2·360
*Mn*6	1·004	2·964	*Al*6	0·990	1·778
*Mn*7	0·923	2·766	*Al*7	1·065	2·244
*Mn*10	0·926	2·155	*Al*8	1·053	2·661
*Mn*11	0·771	1·537	*Al*9	1·034	2·683
*Mn*12	0·810	1·774	*Al*10	1·065	2·524
*Mn*13	0·840	2·569			

Number of sets of observations, $N = 73$; $\Sigma X/N = \overline{X} = 0{\cdot}887$; $\Sigma Y/N = \overline{Y} = 2{\cdot}095$; $\Sigma X^2/N = 0{\cdot}836$; $\Sigma Y^2/N = 4{\cdot}908$; $\Sigma XY/N = 1{\cdot}975$.

$$\sigma_x = \sqrt{\frac{\Sigma X^2}{N} - \overline{X}^2} = 0{\cdot}223$$

$$\sigma_y = \sqrt{\frac{\Sigma Y^2}{N} - \overline{Y}^2} = 0{\cdot}713$$

$$r = \frac{\frac{\Sigma XY}{N} - \overline{X}\overline{Y}}{\sigma_x \sigma_y} = 0{\cdot}724$$

Gradients with respect to X axis of the regression lines, (i) of X on $Y = \frac{\sigma_y}{r\sigma_x} = 4{\cdot}41$; (ii) of Y on $X = \frac{r\sigma_y}{\sigma_x} = 2{\cdot}31$.

Gradient of the bisector of the angle between the regression lines = 3·07.

developed for the investigation of slag–metal reactions has proved highly satisfactory, and appears to be capable of wide application to steel-making problems.

(2) The various empirical methods which have been advanced to predict the amount of dephosphorization occurring in industrial practice break down when applied to the wider range of slag compositions employed in this work.

(3) A linear empirical relationship exists between log (total lime) and the logarithm of the equilibrium constant for the primary phosphorus reaction :

$$2P + 5FeO \rightleftharpoons P_2O_5 + 5Fe,$$

showing that the main factors in dephosphorization are the FeO, CaO, and P_2O_5 contents of the slag. A method of slag control based on this relationship has been indicated, but since the present work was all carried out at 1585 ± 10° C., the curves presented are similarly limited to that range.

(4) This empirical relationship is independent of other variations in slag composition within the wide range examined. Thus the equilibrium relationship is not significantly affected by alumina, at least up to 8%, whilst MnO and MgO appear to act mainly as diluents.

(5) The constituents occurring in rapidly quenched slags are: (*a*) A solid solution of dicalcium silicate with tricalcium phosphate, containing all the SiO_2 and P_2O_5 in the slag; in slags of low basicity, part of the CaO in the silicate may be replaced by MgO. (*b*) Dicalcium ferrite, which might, however, contain alumina in solid solution. (*c*) An oxide phase containing MgO, MnO, and FeO, with possibly some CaO.

(6) The equilibrium constant :

$$K = \frac{(P_2O_5)}{[P]^2(FeO)^5(CaO)^3}$$

has been evaluated by statistical methods on the basis of the most probable constitution of the slag at high temperatures. On the assumption that the slag constituents are equivalent to $3CaO.P_2O_5$, $2CaO.SiO_2$, and $0{\cdot}75CaO.Fe_2O_3$, the best value of K is $2{\cdot}72 \times 10^{-6}$ at 1585 ± 10° C.

ACKNOWLEDGMENTS.

The authors wish to express their great appreciation of the continued encouragement which they have received from Professor J. H. Andrew, D.Sc., during the course of this work. Thanks are also due to Mr. W. H. Wilcockson, of the Department of Geology of the University of Sheffield, for considerable help in the petrographic examination of the slags, and to Dr. W. R. Maddocks and Dr. J. White for many helpful discussions.

The investigation was undertaken for the Ingot Committee of the Joint Research Council, who gave generous financial support, and discussed the work at various stages. Although the authors have benefited greatly from these and other

discussions, they accept complete responsibility for the views expressed in this paper.

REFERENCES.

1. Symposium on Experimental Methods in Study of Steelmaking : *Transactions of the American Institute of Mining and Metallurgical Engineers*, 1940, vol. 140, p. 126.
2. Taylor and Chipman : *Transactions of the American Institute of Mining and Metallurgical Engineers*, 1943, vol. 154, p. 228.
3. Herty : *Transactions of the American Institute of Mining and Metallurgical Engineers*, 1926, vol. 73, p. 1107.
4. Samson-Himmelstjerna : *Archiv für das Eisenhüttenwesen*, 1933, vol. 6, p. 471.
5. Krings and Schackmann : *Zeitschrift für anorganische und allgemeine Chemie*, 1933, vol. 213, p. 161.
6. Maurer and Bischoff : *Archiv für das Eisenhüttenwesen*, 1933, vol. 6, p. 415.
7. Oelsen and Maetz : *Mitteilungen aus dem Kaiser-Wilhelm-Institut für Eisenforschung*, 1941, vol. 23, No. 12, p. 195.
8. Trömel : *Stahl und Eisen*, 1943, vol. 63, p. 21.
9. Lorenz : "Das Gesetz der chemischen Massenwirkung." Leipzig, 1927 : L. Voss.
10. Whiteley : *Proceedings of the Cleveland Institution of Engineers*, 1922, No. 2, p. 36.
11. McCance : *The Iron and Steel Institute*, 1938, *Special Report No.* 22, p. 331.
12. Schenck and Riess : *Archiv für das Eisenhüttenwesen*, 1936, vol. 9, p. 589.
13. Zea : *Journal of The Iron and Steel Institute*, 1945, No. I., p. 459 P.
14. Jackson : *Journal of The Iron and Steel Institute*, 1944, No. I., p. 49 P.
15. Fisher : "Statistical Methods for Research Workers." London, 1941 : Oliver and Boyd.
16. Chipman : *Transactions of the American Society for Metals*, 1942, vol. 39, p. 817.
17. Hansen, Brownmiller, and Bogue : *Journal of the American Chemical Society*, 1928, vol. 50, p. 396.
18. Rait and Goldschmidt : *Journal of The Iron and Steel Institute*, 1945, No. I., p. 391 P.
19. Bredig : *American Mineralogist*, 1943, vol. 28, p. 594.
20. Barrett and McCaughey : *American Mineralogist*, 1942, vol. 27, p. 680.
21. Greene : *Journal of Research of the National Bureau of Standards*, 1944, vol. 32, p. 1.
22. Nagelschmidt : *Journal of the Chemical Society (London)*, 1937, p. 865.
23. Klement and Streckenreiter : *Zeitschrift für anorganische und allgemeine Chemie*, 1940, vol. 245, p. 236.
24. Phemister : *Mineralogical Magazine*, 1942, vol. 26, p. 225.
25. Mason : *Journal of The Iron and Steel Institute*, 1944, No. II., p. 69 P.
26. Schneiderhöhn : *Mitteilungen aus dem Kaiser-Wilhelm-Institut für Eisenforschung*, 1931, vol. 13, p. 109.
27. Bredig : *Journal of Physical Chemistry*, 1942, vol. 46, p. 747.

CORRESPONDENCE.

Dr. T. Fairley (The Park Gate Iron and Steel Co., Ltd.) wrote : The authors say that they found it convenient to keep the lime/silica ratio constant for a given series of melts and to vary the FeO content of the slag, and, therefore, in Fig. 17, which shows the relationship between (FeO) and the $(P_2O_5)/[P]$ ratio for the series *A*, *C*, *D*, and *E*, the points are plotted in groups according to fixed lime/silica ratios. In British basic open-hearth steelmaking practice, where, generally, the P_2O_5 contents of tapping slags are appreciable, the lime/silica ratio does not mean a great deal as regards basicity, and a much better method of expressing basicity is by the ratio $CaO/(SiO_2 + P_2O_5)$. Also, the total iron content of a slag is a good indication of its oxidizing power. Accordingly, I have calculated the values of $CaO/(SiO_2 + P_2O_5)$ and the total equivalent iron for all the slags given by the authors in Table I. These values, for series *A*, *C*, *D*, and *E*, are plotted in Fig. A, and the values of the phosphorus in the metal and the dephosphorizing factors are shown. Fig. B gives similar results for the series *B*, *P*, *Al*, *Mn*, *MnX*, and *MnY*. When plotted in this way the results conform to what is obtained in practical steelmaking, that is, in both Figs. A and B the lowest values for the phosphorus in the metal are obtained when the basicities and oxidizing powers are suitable. For example, in Fig. A, when the total equivalent iron content is greater than 8·5% and less than 21·5% and the $CaO/(SiO_2 + P_2O_5)$ is greater than 1·7, then low phosphorus values are obtained. In the case of the six values in Fig. A where the total equivalent iron content is greater than 23%, the phosphorus removal is not good, but the CaO content of these slags is very low, ranging from 30·4% to 37·2%. Fig. B clearly shows that the lowest values of the phosphorus in the metal are obtained with the higher basicity values when the total equivalent iron is adequate.

At Park Gate we have found that, when using from 40% to 45% of hot metal, the majority of our tapping slags have a total equivalent iron content of 11·5–14·5%, together with $CaO/(SiO_2 + P_2O_5)$ values of 2·5–2·8. The authors do not include any slags within these ranges, and although the conclusions are very interesting, their value would have been greater had the investigation included slags typical of normal steelmaking tapping slags.

Dr. A. H. Jay (Research and Development Department, The United Steel Companies, Ltd., Stocksbridge, near Sheffield) wrote : The subject

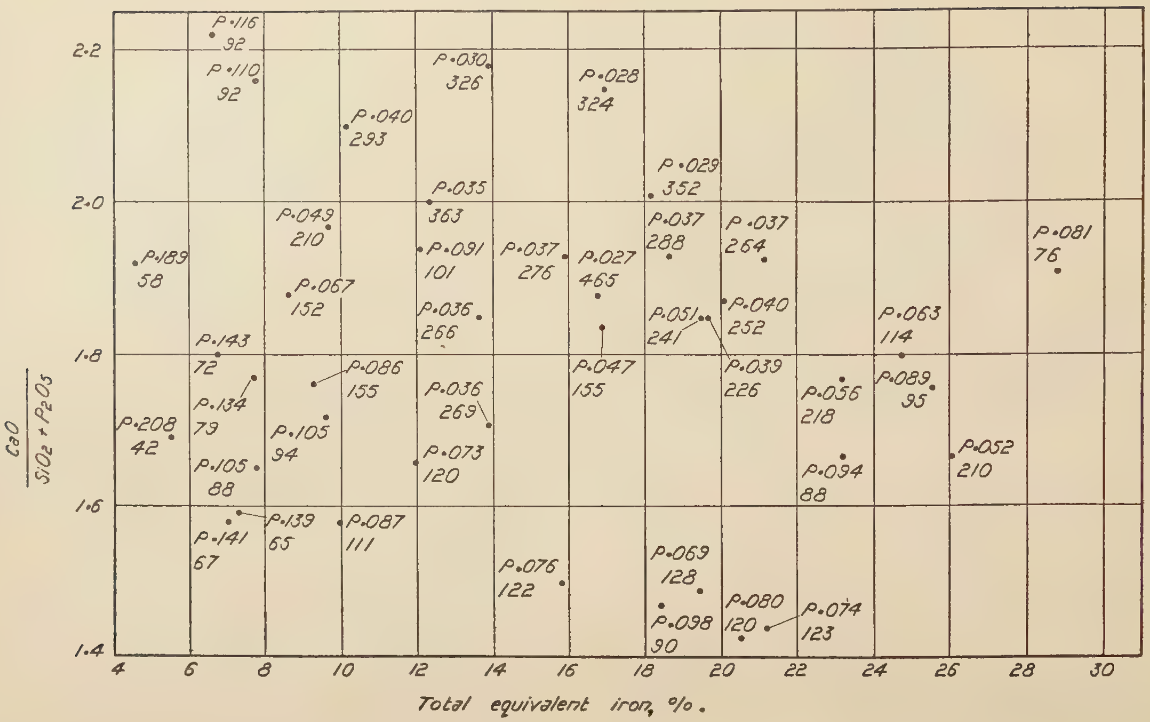


FIG. A.—[P] and Dephosphorizing Factors, Series *A*, *C*, *D*, and *E*.

FIG. B.—[P] and Dephosphorizing Factors, Series *B*, *P*, *Al*, *Mn*, *MnX*, and *MnY*.

of this paper is of great interest to me. I prefer to think of the paper in two parts: (*a*) Experimental and (*b*) analytical.

In my opinion, the experimental portion—designing, making, testing, and using the equipment, and carrying out the necessary analyses—was a first-class piece of work. The work ought to be pursued further to study the effect of temperature and slags more in keeping with the conditions at tapping in industrial open-hearth furnaces.

The analytical portion might be discussed under two headings, graphical and statistical. The graphical representation of some results (*see* Fig. 17) is very instructive in showing the effects of FeO content and increasing CaO/SiO_2 ratio. Results for *A*16, *D*3, and *D*13 are not included in the diagram; what is the reason for their omission? While there is a tendency for the distribution maximum to move to higher FeO content for increasing CaO/SiO_2 ratio, the range 12–18% of FeO would have to be examined in greater detail to decide on this point. Considering the experimental accuracy and the results available, the optimum FeO content is 14%, approximately, for this series. Will the authors explain the purpose of Fig. 18? The curves in Fig. 19 are very interesting. It is difficult to decide whether or not the value for CaO/FeO of 3–4 has any fundamental significance, though this ratio coincides with the position of a phase boundary in the binary system CaO–FeO. Results from tests made to find the effect of MnO suggest to me that it is not merely, as is said on p. 125 P, one "of dilution of the active constituents of the slag" (*see* further comment below). Should not the peak values for curves in Fig. 21 be 310, 265, and 210, approximately (say ± 10)? The effect of alumina on the distribution factor (*see* Figs. 23 and 24) is shown to be very pronounced. I consider that alumina does behave like silica, and welcome this confirmatory evidence. The statement "that the apparent difference in behaviour is not significant from a statistical point of view" is certainly not in agreement with the facts assessed with or without the help of statistics (*see* further comment below). The effect of magnesia in the range 3–14% has not been determined, but an examination of a graph, drawn by myself, of $\sqrt[3]{k}(=P_2O_5/FeO)^5.(P)^2$ plotted against CaO content, based on molecular percentages, shows a systematic grouping of points corresponding to high and low magnesia content with respect to a mean line relating $\sqrt[3]{k}$ and CaO. Clearly, then, magnesia behaves as a base when the lime content is low. (Free, uncombined lime was not found even in the most basic slags examined.)

In the section "Treatment of Results" some previous papers on slag/metal behaviour are discussed and assessed in terms of the authors' data. The authors' conclusion that previous methods for assessing slag/metal behaviour are based primarily on local steelmaking conditions and not strictly on fundamental conceptions is true, but it must be said in fairness to these pioneers that they had to show "workable expressions" in the absence of any real knowledge of slag constitution. Further, in basic steelmaking the majority of slags at tapping have a higher "basicity" than any of those considered by the authors; in other words, steelmaking tapping slags carry lime (free, uncombined, dispersed, fluxed) which is absent in the present slags. The authors' decision to represent the oxidizing power of the slag, with respect to the removal of phosphorus, by the simple expression:

$$2P + 5FeO \rightleftharpoons P_2O_5 + 5Fe$$

is, in my opinion, not open to any serious criticism, since the slags do not contain any uncombined lime. The method permits the effects of MnO, MgO, and Al_2O_3 to be assessed later if and when systematic errors arise due to over-simplification of analytical procedure. Having accepted the fact (source of information not given) of the "formation of a stable phosphate" (p. 137 P) it is a surprise to find that the authors have not tested by their experimental data the expression:

$$3CaO + P_2O_5 \rightleftharpoons 3CaO.P_2O_5$$

instead of having recourse to a determination of the constants for a curve suggestive of the type $y = cx^n$ (p. 137 P). Had the authors proceeded in this way they would have found that their results (molecular basis), apart from the low CaO contents plotted as $\sqrt[3]{k}$ against CaO, substantiated the above expression, *i.e.*, the association of 1 molecule of P_2O_5 to 3 molecules of CaO. (It should be pointed out, however, that the scatter of points would not allow of a distinction between $3CaO.P_2O_5$ and $4CaO.P_2O_5$.) The object of this comment is to draw attention to the type of curve relating the factor *k* and the total lime, rather than the evaluation of a single expression which claims to assess the dephosphorizing power of all slags given in this paper. The expressions are open to criticism, because lime is considered all-important while the effects of MnO, MgO, and Al_2O_3 are dismissed as being insignificant, *i.e.*, errors arising from the simplified treatment are included in the normal experimental error. This procedure is disappointing in view of the object of the research, *viz.*, the fundamentals governing the removal of phosphorus. With regard to the numerical values in the equations, are not several in error? Considering the possible effects of MnO, MgO, and Al_2O_3, magnesia has already been discussed. (Incidentally, magnesia

can exert a pronounced effect in industrial furnaces.*)

A comparison of observed and calculated phosphorus contents (use has been made of the authors' equations) shows the effects of MnO and Al_2O_3. Examination of the positive and negative errors suggests the following comments:

Series A, B, C, D, *and* E.—Errors positive and negative, not systematic.

Series A1 (*high* Al_2O_3).—Errors all in same direction, therefore systematic, and effect of Al_2O_3 can be assessed.

Series P, Mn, *and* MnX (*medium* MnO).—Errors show trend in one direction.

Series MnY (*high MnO*).—Errors all in same direction, therefore systematic, and effect of MnO can be assessed.

The above facts, together with a further study of Schenck and Reiss' work, should convince the authors that their opinion of the value of that work has been hurriedly formed.

A point suggested by the paper, from the straight-line relationships, Figs. 32 and 33, is the feasibility of extrapolation to higher lime contents. It is my opinion that this extrapolation is dangerous. It certainly would not agree with my experience of industrial metal and slag samples. The reason is clear to me, namely, that the oxidizing power of the slag is not given under all conditions by the numerical value of FeO or total iron contents, but is reduced markedly when free lime is present, owing to absorption of FeO in the lime (solid solution).

The last section of the paper attempts to determine the state or constitution of the slag at working temperatures. Two points call for comment: Will the authors define their use of the term "free lime"? (Obviously it is something not visible under the microscope nor found on their X-ray photographs.) Will the authors give reasons for assessing the affinity of CaO for P_2O_5 on the basis of the lime which is to be considered free (presumably uncombined or surplus)?

To sum up I would say that the experimental work is good, but the analytical treatment is disappointing.

Should it be possible to pursue the work, I suggest the following points for consideration:

(1) Examination of slags which contain uncombined lime:

(*a*) Medium/high silica, low/medium phosphorus pentoxide, *e.g.*, CaO, 52%; SiO_2, 12%; P_2O_5, 6%; MnO, 6%; Al_2O_3, 1%; MgO, 6%; FeO, 10%; Fe_2O_3, 5%.

(*b*) Low/medium silica, high phosphorus pentoxide, *e.g.*, CaO, 46%; SiO_2, 8%; P_2O_5, 16%; MnO, &c., as above.

(2) Repeat a number of slags at other temperatures, up to, say, 1630° C.

(3) Do not expect straight-line relationships to account for the behaviour of all slags.

AUTHORS' REPLY.

The AUTHORS wrote in reply: We are grateful to Dr. Fairley and Dr. Jay for having contributed to the discussion.

Dr. Fairley's confirmation that the laboratory results submitted are in keeping with practical experience is welcomed, and we shall look forward to hearing if the suggested linear relationship between log ΣCaO and log k fits in with industrial data. Any simple method of expressing basicity must be arbitrary and it was realized that the lime/silica ratio which we employed could not represent the basic power of the slag in any exact manner. It should be remembered that in any one series of melts the flux content of the slags was maintained constant, and when the FeO content was varied the CaO and SiO_2 contents were adjusted in such a manner that the CaO/SiO_2 ratio was unchanged. Bearing this in mind, it will be seen that for a given flux content the behaviour of a series of slags at a given temperature can be completely described if $(P_2O_5)/[P]$ is plotted against (FeO) for a given CaO/SiO_2 ratio. As pointed out in the paper, the total iron content can be used instead of the analytically determined FeO if desired.

The empirical nature of the basicity factor used by Dr. Fairley is emphasized by the fact that, in accounting for the six exceptions in his Fig. A, he finds it necessary to refer to the low CaO content of the corresponding slags. If the basicity factor were truly satisfactory it should compensate for such variations in lime content.

It is unfortunate that our slag compositions did not quite cover the range of tapping slags, but in our early experiments we found that slags of higher lime content than those employed were unduly viscous and might not readily reach equilibrium conditions. With the experience now

* A. H. JAY, *Journal of The Iron and Steel Institute*, 1945, No. I., p. 505 P.

available, however, there is no reason why the investigation should not be extended to the higher lime region, provided that sufficient time is allowed for the equilibrium conditions to be attained.

We are grateful to Dr. Jay for drawing attention to the omission of three experimental points from Fig. 17; this was accidental, as he no doubt realized on plotting the missing points. The purpose of Fig. 18 is explained in the text, but unfortunately some misunderstanding may have resulted from an error which occurred in the diagram reproduced in the advance copy of the paper; the diagram as now reproduced is correct. It is unlikely that the CaO/FeO ratio in Fig. 19 has any fundamental significance, since it is accepted that CaO and FeO do not form a true binary system. Fig. 19 does show, however, that the combined effect of CaO and FeO on dephosphorization is most pronounced when the ratio of CaO/FeO is between 3 and 4. The curves in Fig. 21 might have been drawn through the peak values suggested by Dr. Jay, but this would in no way have affected the deductions drawn therefrom.

There is a tendency for MgO to increase the value of k for a particular value of CaO in the series *A*, *B*, *C*, *D*, and *E*, but this effect is not apparent in the *Mn*, *MnX*, and *MnY* series. Bearing in mind the fact that part of the lime is fixed by the P_2O_5 as a lime silico-phosphate, and to avoid the complicating effect of this constituent which is already included in the k expression, it would be more appropriate to plot $\log k + 5$ against $\log (CaO - 3P_2O_5)$ on a molecular per cent basis in assessing the total effects of the other constituents. By plotting the results in this manner the linear relationship for the series *A*, *B*, *C*, *D*, and *E* would be subject to the effect of only two varying constituents, *i.e.*, MgO and SiO_2, since the Fe_2O_3, MnO, and Al_2O_3 for these series are approximately constant. When this is done the results show no tendency to group themselves according to the corresponding MgO and SiO_2 contents. As for the effect of MnO, it was shown that by plotting $\log k + 5$ against $\log \Sigma CaO$ on the molecular per cent basis, all the points of the high MnO series grouped in well with the other results. Within the experimental error these points distributed themselves on both sides of the mean line, and the mean discrepancy between the actual and calculated phosphorus contents is 0·008 on the atomic per cent basis, which is equivalent to approximately 0·004% by weight. This order of discrepancy is within the error of the actual analytical determination of phosphorus.

Work since carried out by two of the authors (K. B. and P. V.) on the phosphorus reaction at a number of other temperatures shows that MgO and MnO do not affect the relationship, and that the results for each temperature can be represented by a straight line parallel to that reported for 1585° C. in the present work. This work is now in course of publication. We are justified therefore in concluding that MgO and MnO, at least up to the limit of basic practice, do not influence the relationship suggested in the paper.

In dealing with the effect of alumina, Dr. Jay seems to have confused the terms "not significant," in the statistical sense, with "insignificant" as used in everyday speech. They are related in much the same way as "not proven" and "not guilty" in Scottish law. On the evidence at present available it is not possible to prove that alumina has any direct effect upon the process of dephosphorization, but further evidence may enable a more definite verdict to be returned. In the meantime, the fact that we have not summarily dismissed the chemical effect of alumina is clearly stated in the text, and in including the slags containing up to 8 wt.-% of Al_2O_3, we were well aware that some error was involved, but the statistical test showed this error to be within the experimental accuracy. Equations (4) and (5) can therefore be used in the control of the slags to which bauxite flux up to this limit is added instead of fluorspar.

It cannot be too strongly stressed that the linear relationship between $\log k$ and $\log \Sigma CaO$ is empirical, having no direct theoretical basis, and that the fundamental nature of the phosphorus reaction cannot be elucidated satisfactorily in the absence of real knowledge of the liquid-slag constitution. The straight-line relationship, however, does afford a simple picture of the dephosphorization process from a practical point of view.

It would be interesting to know on how many slag and metal analyses obtained under satisfactory conditions Dr. Jay bases his contention that it would be dangerous to extrapolate the linear relationship to higher lime contents. Even with the strictest control over methods of sampling and analysis—and Dr. Jay does not suggest that our experimental techniques were in any way inferior to current industrial practice—appreciable scatter of the experimental results occurs, and many points were necessary to determine the straight-line relationships of Figs. 32 and 33 with assurance; even more would be necessary in order to be dogmatic as to the validity of extrapolation to higher lime contents. So few slag/metal analyses with corresponding temperatures are reported in the literature that it was impossible for us to check our findings with industrial results, and therefore if Dr. Jay has available the large number of results which would be necessary to justify his confidence, we suggest that he and his firm would be doing the steel industry a real service by publishing them.

As a matter of interest to those who wish to test the suggested relationship it should be mentioned that 15 melts with temperatures between 1570°

and 1600° C., from a paper by Zea,* have been plotted on the basis of total FeO, and the points group themselves at the top end of the straight line given in Fig. 33 of our paper, thus showing that the linear relationship is still valid in this range of industrial refining and tapping slags.

Dr. Jay has queried the accuracy of the numerical constants in some of the equations; we can only say that these figures were derived by means of the normal method of least squares, using a calculating machine, and that check determinations were carried out.

In dealing with the methods proposed by previous workers on the subject, we have due respect for these pioneers, but the scientific spirit demands that one be impersonal and that there should be no hesitation in stating facts. The earlier methods have been fairly discussed and shown to be applicable over certain ranges of slag compositions. In assessing the value of Schenck and Riess' method, full consideration should be given to the assumptions on which it is based, and Dr. Jay himself must admit that they are contrary even to his own experimental evidence.

The oxidation of phosphorus by FeO given in equation (1) represents only one stage of the complete phosphorus reaction, as is shown by the fact that the value of k based on this equation is not a constant. Our assumption that a stable phosphate is formed is well supported by our experimental evidence and more explicitly by the work of Oelsen and Maetz (*see* reference 7 of the paper) and of Trömel (*see* references 7 and 8, respectively, of the paper). Dr. Jay's substantiation of the expression $3CaO + P_2O_5 \rightleftharpoons 3CaO.P_2O_5$ is unsound from the physico-chemical point of view; firstly, because the CaO in his expression is not "free" and, secondly, because this way of plotting is merely another version of the method suggested in the paper, and examination of the points obviously indicates the relationship of the type $y = cx^n$ and not a straight line as he imagines. Equation (8) shows that the value of n is about 14, and taking the cube root of the equation $y = cx^{14}$ cannot possibly result in a linear relationship except to a crude first approximation.

The term "free lime" mentioned in the last section of the paper refers to the lime which is in excess of the amount necessary to combine with SiO_2, P_2O_5, and Fe_2O_3, in the relations assumed. The fact that the free lime is not present as a separate phase in the slag after solidification is not difficult to explain. A limited amount may be present in the oxide phase as solid solution, as suggested by Rait and Goldschmidt (*see* reference 18 of the paper); a further quantity may be combined in the form of a ferrite–aluminate phase on cooling, and there is the possibility of the formation of a separate aluminate phase existing in the solid slag, but not in sufficient quantity to be detected by X-ray and microscopic examination.

Concerning our assessment of the affinity of CaO for P_2O_5 on the basis of the lime which is to be considered "free," we would refer Dr. Jay to p. 143 P; we believe that, bearing in mind the law of mass action, he will have no difficulty in understanding our reasons for this procedure.

We are grateful to have Dr. Jay's suggestions for future work. As he will have gathered, some of these items have already been dealt with and the results will soon be published With regard to the others, we should like to suggest that the technique which we developed has proved itself and there is no good reason why workers in industrial laboratories with a real interest in the physical chemistry of steelmaking should not apply this method to their own problems.

* Zea, *Journal of The Iron and Steel Institute*, 1945, No. I., p. 459 P.

FUEL PROBLEMS IN THE SWEDISH IRON AND STEEL INDUSTRY.*

By Dr. MAGNUS TIGERSCHIÖLD (Jernkontoret, Stockholm, Sweden).

Synopsis.

The evolution of the Swedish iron and steel industry and the mineralogical, historical, and economic factors affecting that evolution are briefly discussed.

The occupation of Norway by the Germans in 1940 *completely isolated Sweden from British and American sources of imports; with little or no suitable native resources of coal, petrol, or fuel-oil, the position of Swedish industry in regard to fuel supplies was critical. Fuel economy became a paramount necessity and industry went over to the use of substitutes, such materials as wood, charcoal, and pressed-straw bales being used as metallurgical fuels. Equipment and methods were altered and new equipment and methods were devised to meet the situation, with striking results.*

The present state and the future prospects of the Swedish iron and steel industry are discussed. Sweden's natural advantages of large resources of pure iron ore and relatively great supplies of hydro-electric power have led to the adoption of special methods for reduction. The use of 100% *sintered concentrates in the coke blast-furnaces has resulted in a very low consumption of coke. The rich concentrates have proved to be an excellent raw material for sponge-iron production, and the Höganäs and Wiberg processes and their future place in the Swedish iron and steel industry are considered.*

I.—Introduction.

The scope of this paper being to review the fuel problems in the Swedish iron and steel industry, it is considered necessary first to give a brief outline of the development of that industry, together with its present structure.

Formerly the conditions for a Swedish iron and steel industry were extremely good. The iron-ore resources are very large in comparison with the size of the country, charcoal could be produced at a low price almost everywhere, and water-power could easily be derived from the many streams and rivers. From ancient times until the last decades of the 19th century the structure of the Swedish iron and steel industry remained broadly the same, consisting of very many small units located in places where iron ore, charcoal, and water power were available.

Before the introduction of coke and coal for the production of iron and steel, charcoal and wood were the only fuels used for this purpose, and Sweden held a very strong position in the iron and steel production of the world. During the first half of the 18th century no less than 35% of the world's iron and steel was made in Sweden, *i.e.*, about the same proportion of the world production as that of the United States during 1930 and subsequent years up to the outbreak of war. But as soon as coke was used more frequently as blast-furnace fuel, the dominating position of Sweden ended and to-day she produces less than 1% of the world production of iron and steel; on the other hand, the tonnage produced in Sweden to-day is more than fifteen times as great as it was in the middle of the 18th century.

The introduction of the puddling process in Britain was a severe blow to Swedish iron and steel production, and when in 1860 the Bessemer and open-hearth processes began their triumphal progress throughout the world the position of the Swedish iron and steel industry was again severely threatened. The small units (at that time mostly charcoal-fired Lancashire hearths for wrought-iron production) had to be replaced by much larger furnaces, and the water-driven hammers were replaced one after another by rolling mills, with greater production and much higher installation costs. Most of the Swedish ironworks were privately or family owned, and many of them could not raise the money necessary for the building of open-hearth furnaces, Bessemer plants, and rolling mills. However, companies were formed which modernized the most favourably located works, while many other plants had to go out of production.

At that time the Swedish iron and steel industry changed over more definitely to quality-steel production, there being strong natural reasons for such a development. From the high-grade native ores and charcoal, both free from contamination, a pig iron was produced which

* Received February 1, 1946.

formed the "virgin" basis for Swedish production of quality steel; the possession of successive generations of highly skilled workmen, foremen, metallurgists, and engineers, all of them having the sense of quality in their blood, has also been a great advantage.

It is worth mentioning that formerly very few new metallurgical processes were originated in Sweden, but on the other hand foreign processes were rapidly adapted and skilfully developed to suit Swedish conditions. It is characteristic that in Sweden the acid Bessemer as well as the acid

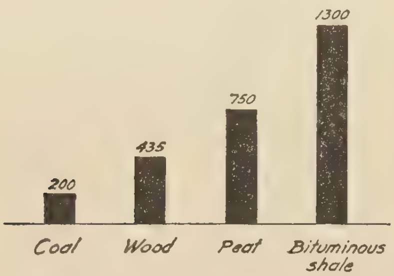


Fig. 1.—Fuel Resources of Sweden, converted into coal-equivalents. (Figures represent millions of tons.)

open-hearth processes were developed especially for quality-steel production at an early stage, the Bessemer process through the great work of Göransson at Edsken and Sandviken, and the acid open-hearth process by Lundin at Munkfors. Subsequently, much has also been done in the development of electric steel furnaces for quality-steel production.

As an example of the rationalization process mentioned above, the number of blast-furnaces, which in the year 1870 amounted to 215, had diminished to 135 by 1900, while to-day there are only about 50 blast-furnaces in operation in the entire country.

It is quite understandable that Sweden had, and always will have, great difficulties in competing with the large iron- and steel-producing countries of the world in the manufacture of commercial steel. One of the chief reasons for this is that there are no coal resources in Sweden worth mentioning (the fuel resources of the country are graphically shown in Fig. 1). It is of interest to point out that Sweden's greatest resources in heat units are her extensive layers of bituminous oil-bearing shales. During this last war a large plant for the distillation of oil from shales was built and put into production, but there is very little hope that supplies from such a source can be economically utilized under normal conditions.

The peat moors, which form the next largest resource of fuel in Sweden, can also be utilized under war-time conditions only; in such circumstances, they at least form a very good reserve. Last year the production of peat was raised to $1\frac{1}{4}$ million tons,* which corresponds to about 600,000 tons of coal.

Fully to understand Fig. 1, it must be mentioned that the annual regrowth of the Swedish forests corresponds in heat value to about 14 million tons of coal. The continuous rise in labour costs makes the use of wood or charcoal as fuel for the iron and steel industry more and more expensive. The forests have been severely depleted during the war, and under normal conditions they must be reserved for the production of timber, pulp, and chemicals, where the use of wood is much more economical. The total consumption, production, and imports of fuel

Table I.—*Swedish Consumption, Production, and Imports of Fuel*, 1939.

Consumption.	Coal, × 1000 tons.	Coke, × 1000 tons.	Oil for Fuel and Engines, × 1000 tons.	Petrol and Wood Alcohol, × 1000 gal.	Wood (loose vol.), × 1000 cu. ft.	Peat, × 1000 tons.	Coal Equivalent, × 1000 tons.
Industry	3,500	610	60	...	53,400	...	...
For generation of electric power	320	...	...	...	...	...	...
For generation of city gas	810	...	...	...	...	...	...
For production of charcoal	...	...	...	...	132,200	...	...
For railways, automobiles, and marine purposes	1,040	20	450	172,600 (petrol) 8,800 (alcohol)	700	...	...
For heating of homes and buildings; home-industries	760	2,260	200	...	631,000	26	...
Total	6,430	2,890	710	181,400	817,300	26	...
Produced in Sweden	440	530	...	8,800	817,300	26	...
Imported	5,990	2,360	710	172,600	...	...	...
Coal equivalent of total	6,430	2,890	1,140	950	3,250	13	14,670

* Unless otherwise stated in the text, figures, or tables, avoirdupois units of weight measurement are to be understood.

in 1939 are given in Table I., together with the coal equivalent of the different fuels; the dependence of Sweden upon the importation of fuel, owing to the smallness or expense of utilization of her own resources, is evident.

On the other hand, Sweden has a great advantage in her relatively large resources of water-power; the annual output of hydro-electric power since 1890 is shown graphically in Fig. 2. The total

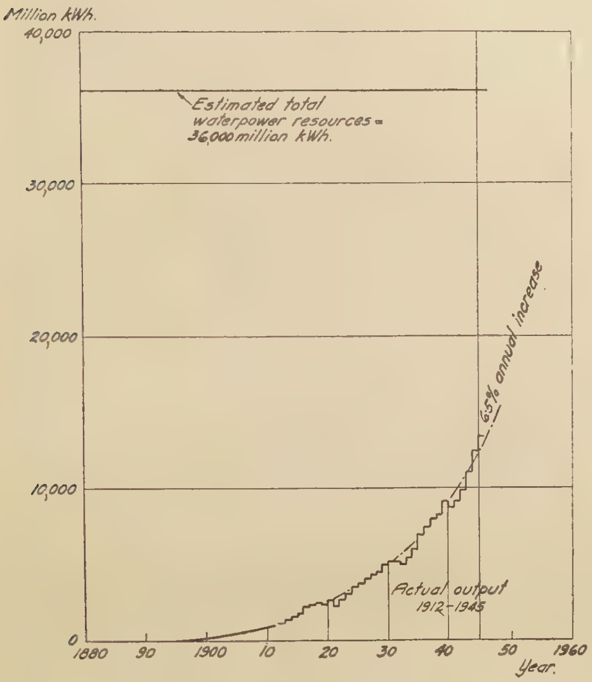


Fig. 2.—Output and Estimated Resources of Hydro-Electric Power in Sweden.

potential hydro-electric-power resources in Sweden have been estimated at 36,000 million kWh. Two-thirds of this amount could be developed at reasonable cost, but the remaining third will be more expensive to exploit and the last part of it may never be utilized. It has been much discussed how the curve shown in Fig. 2 will continue. If it should rise in the same way as hitherto, the best two-thirds of the water power will most likely be exploited before the year 1955. About that year the curve will most probably alter direction and more or less asymptotically approach the value of 36,000 million kWh. Reference will again be made to these problems later in the paper, but an account of the development and present structure of the Swedish iron and steel industry may be appropriate at this point.

The total annual Swedish pig-iron production for the years 1900 to 1944, together with the percentage of the total output contributed by different methods of manufacture, is shown in Fig. 3. The most remarkable fact is that the production of coke pig iron has been raised to about the same amount as that of charcoal pig iron. The production of electric pig iron has not been increased since 1920, but now the output from the new Government-owned plant at Luleå will raise the production of electric pig iron by 60,000–90,000 tons per annum.

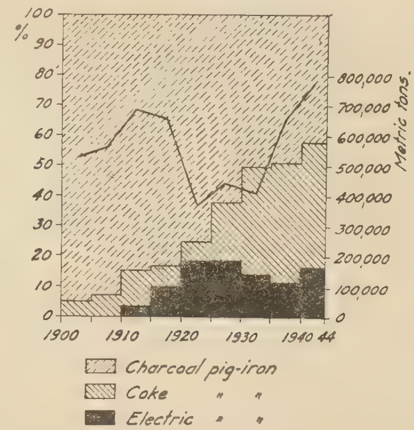


Fig. 3.—Total Annual Production of Pig Iron (metric tons) in Sweden from 1900 to 1944 and production (percentage of total) by different methods of manufacture.

The production of steel ingots, castings, and wrought iron since 1860 and the output by different methods of present manufacture are shown in Fig. 4. The diagram is very interesting,

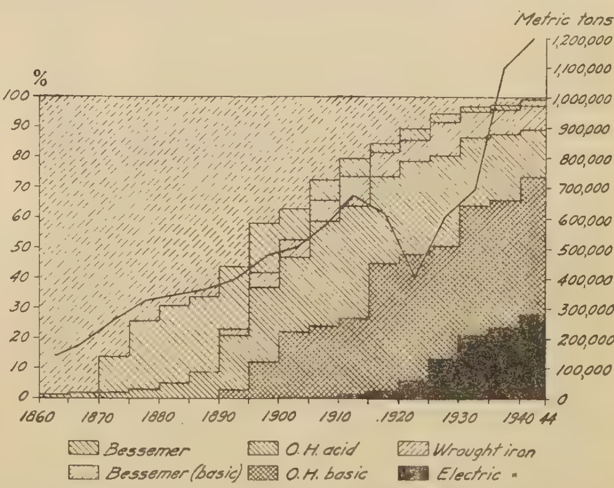


Fig. 4.—Total Annual Production of Ingots, Castings, and Wrought Iron (metric tons) in Sweden from 1860 to 1942 and production (percentage of total) by different methods of manufacture.

showing how the manufacture of wrought iron, which was the dominating product in 1860, has diminished to almost zero in recent years. The production of acid Bessemer steel expanded rapidly from 1870 to 1890 but has since then dropped; it would appear, however, that a renaissance of this method will occur. The pro-

duction of Thomas (mild) steel has increased steadily and will increase still more. At first sight it looks as if the percentage of this production has diminished, but this is not in fact a true picture as about half of the Thomas metal produced to-day is transferred to the electric furnaces for refining and is considered as electric steel in this diagram. Production from the basic open-hearth has grown steadily and at about the same pace as that of electric steel.

The picture of the Swedish iron and steel industry for the two years 1937 and 1943 is given in an instructive form in Figs. 5 and 6. It is well known, however, that statistics for disconnected years are never very representative, and for that reason it is necessary to give average figures of the most important items for some of the years.

In the years before the war the annual production of pig iron was about 600,000 tons, while the imports of coke pig iron amounted to 120,000 tons. The export of charcoal pig iron was, on the other hand, about 80,000 tons. The production of rolled iron and steel amounted to 700,000 tons, of which quantity about 200,000 tons were exported. Swedish imports of commercial steel have varied; in 1937 they amounted to nearly 600,000 tons, but the average figure before the war was about 400,000 tons. During the war the situation changed completely. The

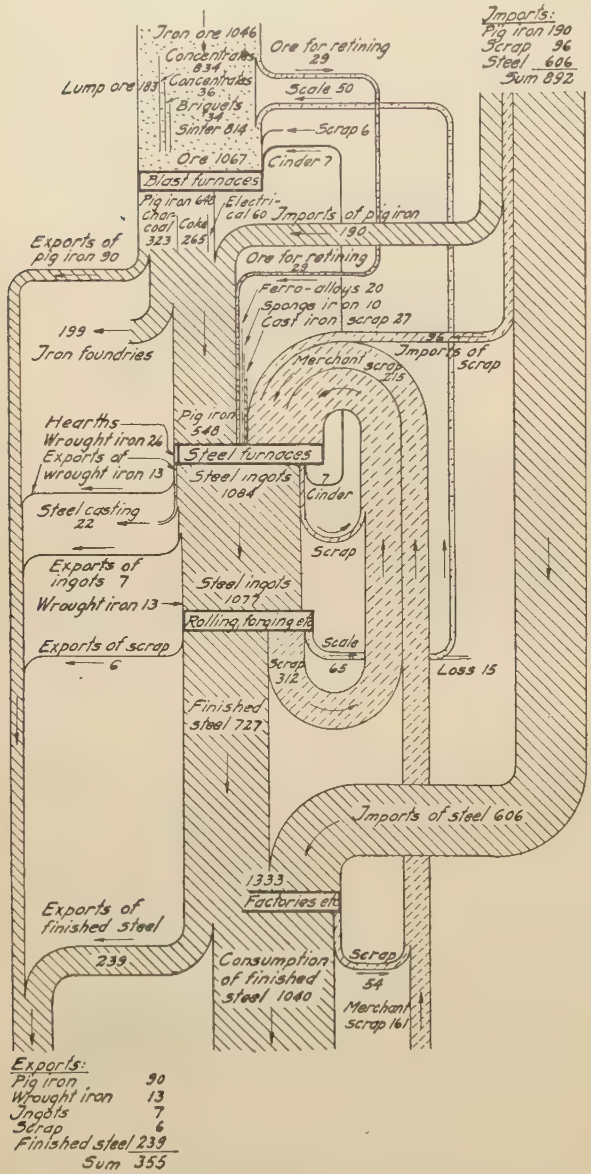


FIG. 5.—Flow of Iron (thousands of metric tons) through Swedish Industry in 1937.

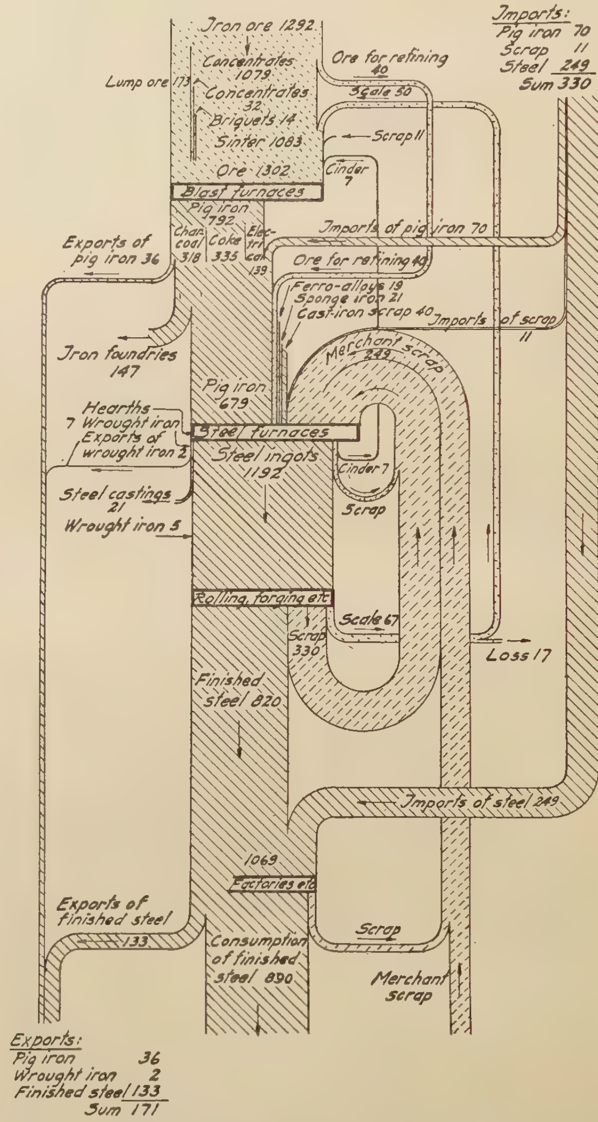


FIG. 6.—Flow of Iron (thousands of metric tons) through Swedish Industry in 1944.

production of pig iron was raised to an average of 800,000 tons, while the import of pig iron progressively dropped to about 15,000 tons and the export of pig iron amounted only to a few thousand tons. The production of rolled iron and steel was increased to slightly below 900,000 tons, while the export of quality steel decreased to about 100,000 tons. The import of commercial steel also decreased; in 1942 it was about 250,000 tons and in 1945 only 30,000 tons.

The annual consumption of finished steel, which in the middle of the nineteen-thirties was about 900,000 tons, increased to 1,000,000 tons in 1942, but dropped again (to about 800,000 tons) in 1945. These figures show that although Sweden has been able to raise her production of steel from 700,000 to about 900,000 tons, this increase did not balance the decrease in imported steel, despite the fact that the exports of steel were reduced by 50%. There was (and still is) a considerable shortage of steel in Sweden, which shortage, as in most other countries during the war, has hit the building trade. Though the quantity of steel available for consumption in the first years of the war increased, the supply for civilian purposes was already at that time insufficient, because of the necessity of building up the military defence of the nation.

It will be obvious that, to quite a large extent, the Swedish quality-steel industry was forced to change to the manufacture of commercial steel. The price of the latter product naturally had to be raised, as a great part of it had to be manufactured from charcoal pig iron. To this, the high prices of wood used for open-hearth furnaces and reheating furnaces must be added. While the price of coal in Sweden before the war was about Kr.30 * per ton, the price of the corresponding quantity of wood has been three or four times as high during the war.

II.—The Provision of Fuel for the Swedish Iron and Steel Industry during the War.

The increase of the production of the Swedish iron and steel works during the war, despite the continually decreasing supply of imported fuel, must be regarded as one of the greatest contributions made to the industry by Swedish engineers. As can be seen from Table I., the normal annual imports of coal and coke amounted to about 6 million and 2·4 million tons respectively; the consumption of coal in the Swedish iron and steel industry reached about 600,000 tons in 1939. The State Commission for fuel supply during the war granted the iron and steel industry the following percentages of its normal consumption of coal :

1st July, 1940–30th June, 1941 . .	67%
1st July, 1941–30th June, 1944 . .	30%
1st July, 1944–31st Dec., 1944 . .	27%
1st Jan., 1945–30th June, 1945 . .	15%
1st July, 1945– . . .	7·5%

At the time of writing (January 1946), the ration is still at the low level of 7·5% of the normal consumption, but it is hoped soon to procure more coal from abroad, including Britain.

The occupation of Norway by the Germans in 1940 shut Sweden off completely from British and American sources of imports, necessitating the finding of substitutes for petrol and oil; at the same time Swedish imports of commercial steel, pig iron, and merchant scrap were cut down to a very low percentage of the pre-war figures. The re-adjustment of Swedish industry to permit the use of wood as the main source of fuel has been a gigantic feat of organization and technical ingenuity.

The use of coke for domestic heating purposes was reduced to a small fraction of the pre-war quantity, what coke there was being reserved mainly for industrial purposes, especially for the coke blast-furnaces. All automobiles, trucks, and buses had to be driven by producer gas generated from wood and charcoal; in certain cases (especially in marine engines) wood-tar also was used as a motor fuel. Practically all of the steam locomotives went over to the use of wood or peat; fortunately the electrification of the railways had been already effected to quite a large extent before the war, and in recent years this work has been intensified.

All the open-hearth furnaces, and the main part of the reheating furnaces for the rolling mills, had to use wood as fuel; many experiments had to be carried out and modifications of the plant made, before the technique of economically heating these furnaces with such low-grade fuel was mastered. It was found that preheating of the secondary air was a great help and that the so-called reversed combustion in the built-in producers of the heating furnaces gave a higher flame temperature.

By the autumn of 1945 the situation had become most difficult, and straw (from rye, oats, and wheat) was introduced as a fuel in the iron and steel works. At one plant as much as 20% of the total fuel used consisted of pressed-straw bales, and an old blast-furnace was rebuilt as a gas producer, using this material as fuel; this producer is operated with hot blast, and slag is tapped off in the molten state. One open-hearth furnace and several reheating furnaces are still heated with gas from this source.

* The monetary unit used throughout this paper is the Swedish Crown, or Krona (Kr.), the present (January 1946) value of which is 1*s.* 2½*d.*

Often the most difficult problems were to transport the wood out of the forests and to get labour to cut the great quantities necessary. In order to get charcoal for automobiles, &c., a large number of kilns were erected, where the tar and other by-products were utilized and in some cases made into lubricants. The annual production of charcoal (before the war about 290,000 tons) was raised to about 850,000 tons, of which amount about 350,000 tons were used in the blast-furnaces and 490,000 tons for the propulsion of automobiles, trucks, and buses. The quantity of wood used directly for the latter purpose was of about the same magnitude, reckoned in heat units.

The achievement of the level of production attained and the maintenance of that production would have been impossible but for small imports of coke and coal from abroad, and for the fact that a great proportion of the wood intended for the pulp industry was available for use as fuel (the export of wood-pulp during the war naturally fell to a very low figure).

Fortunately the water supply during the last three years was exceptionally good, so that a very high output of energy was obtained from the hydro-electric stations. Many electric steel furnaces and annealing furnaces were built during the war, but, owing to the shortage of graphite electrodes, hydro-electric power could not be utilized to the full extent in the steel furnaces.

Fuel Economy in Swedish Blast-Furnaces.

It is a well-known fact that the fuel consumption per ton of product in the blast-furnace diminishes as the iron content of the burden increases. The Swedish magnetite ores are easily concentrated, and it was found economical to use such concentrates in sintered form in the blast-furnaces in amounts of up to nearly 100% of the total ore burden. By this and other means it has been possible to reduce the charcoal consumption, which in 1900 was 25 cwt./ton (72 hectolitres/metric ton), to an average of about 15 cwt./ton (45 hectolitres/metric ton). At the same time the production from the blast-furnaces has been increased from an average of 4000 tons per unit per year to as much as 30,000 tons for the largest of the charcoal furnaces.

The coke blast-furnaces have followed the same trend, with the result that to-day the distinction of producing iron with a coke consumption lower than anywhere else in the world is held by the Swedish blast-furnaces. At one plant making Thomas (basic) pig iron the coke consumption has been brought down to 13 cwt./ton (650 kg./metric ton) of iron, the ore burden consisting exclusively of sintered concentrates. Because of the richness of the burden, the slag quantity is only 940 lb./ton (420 kg./metric ton) of pig iron. The blast temperature is held at about 1380° F. (750° C.). The furnaces in question are only 54 ft. 7 in. (16·5 m.) high, and the production is approximately 200 tons per day per furnace.

A remarkable innovation is that at many Swedish blast-furnace plants to-day the main part of the limestone requirement of the burden is mixed with the ore concentrates before sintering. By this measure a saving of about 110 lb. (50 kg.) of coke per ton of pig iron has been obtained. This good result is also to a large extent attributable to the quality of the sinter now produced. The sinter must not be too hard-burned and its structure must be porous and similar to that of coke. If certain measures are taken it is possible to obtain quite a strong sinter (strength is also essential) and at the same time lower the consumption of coke fines in the sintering process. Formerly about 7% of coke fines were used per ton of sinter produced, but this figure has been brought down to about 4%. Another advantage is that, by the mixing of the limestone with the ore concentrates before sintering, the consumption of lime can be reduced. In Swedish coke blast-furnaces the amount of limestone required for addition to the ore burden has been in some cases brought down to about 11% of that burden. An excellent paper upon sinter production in Sweden has been written by Hessle;* Fig. 22 of that paper shows the difference between the two kinds of sinter mentioned, one being very hard-burned and therefore difficult to reduce, while the other is porous, highly oxidized, and easily reducible.

At any reconstruction of the blast-furnaces during the period of the war, opportunity was taken to increase the hearth diameter, but the bosh diameter was not altered, and the hearth-diameter/bosh-diameter ratio is often as low as 1·15 or 1·20; this applies both to charcoal and coke blast-furnaces.

Great care is taken to maintain a chemically uniform as well as physically uniform burden. Many experiments in the construction and operation of the charging gear have been made in order to get the correct distribution of coke and ore in the furnace. The great economies that can be effected by skilful mechanical maintenance, by precise control of the furnace as regards coke consumption, and by the production of a pig iron of uniform analysis, are really astonishing.

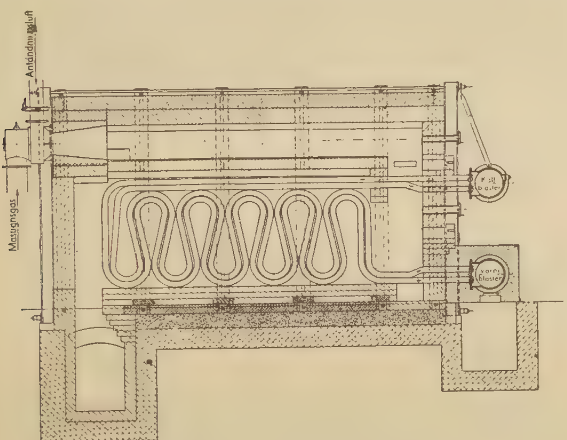
As has already been mentioned, the fuel consumption in the charcoal furnaces has also been brought down to a very low figure. In the best furnaces a consumption of 13–14 cwt. (40 hectolitres) of charcoal per ton of pig iron is expected when sintered ore is exclusively used and the

* *Jernkontorets Annaler*, 1945, vol. 129, pp. 383–446. (The Iron and Steel Institute, Translation No. 289.)

blast temperature is held at about 1110° F. (600° C.).

The low coke and charcoal consumption in the Swedish blast-furnaces naturally results in a low heat value of the blast-furnace gas, this value being very often as low as 84 B.Th.U/cu.ft. (750 kg.cal./cu.m.). The quantity of gas naturally also decreases and in the best furnaces this quantity falls to about 78,000 cu. ft. (2200 cu. m.) per ton of pig iron.

In a country where fuel is expensive, it is very important that the blast-furnace gas be used economically and completely. For heating the blast, regenerative-brickwork hot-blast stoves are used at only two plants in Sweden. At all of the charcoal blast-furnaces, and at several of the coke blast-furnaces, metallic recuperators are used for preheating the blast. With metallic recuperators made from heat-resisting steels it is possible to reach blast temperatures of 1290° F. (700° C.), and with the latest constructions possibly 1470° F. (800° C.). The metallic recuperators are cheaper to instal, but their maintenance costs are probably somewhat higher than those for the firebrick stoves; the former have the great advantage of being very easy to maintain and they are working with the high thermal efficiency of about 70%. The construction of the Lindblom type of recuperator (manufactured at Sandviken) is shown in Fig. 7.



Masugnsgas = Blast-furnace gas.
Antändningsluft = Combustion air.
Kallbläster = Cold blast.
Varmbläster = Hot blast.

FIG. 7.—Lindblom-Type Air-Preheater.

Practically all of the Swedish charcoal blast-furnaces to-day are using Lindblom-type recuperators for heating the blast. The heating element consists of a number (generally nine to twenty-four) of parallel double coils, made of heat-resisting steel, arranged as shown in Fig. 7. The blast-furnace gas is led through a burner to a combustion chamber placed over the heating elements; it then passes the heating coils on its way to the stack. The cold blast is conducted into the preheater, first in parallel flow, but afterwards changing to counter current. This arrangement is of great advantage, as the hot combustion gases have to pass a screen of cold tubes before meeting the hottest part of the coils in counter current; the construction of the coils permits expansion. The apparatus has been built in sizes of from 1075 to 3230 sq. ft. (100 to 300 sq. m.) of heating surface. Generally, a heat-transmission factor of 2 B.Th.U./sq.ft./hr./°F. (10 kg.cal./sq.m./hr./°C.) is obtained, which implies a mean heat-transmission by the tube surface of about 1500 B.Th.U./sq.ft. (4000 kg.cal./sq.m.) per hour. On the gas side the heat transmission is achieved by a combination of radiation and convection and on the air side, naturally, by convection only. The air velocity is kept at about 65 ft./sec. (20 m./sec.). If the blast temperature be kept below 1110° F. (600° C.), the life of the tubes, when they are made of a good heat-resisting steel, seems to be indefinite. At higher temperatures the hottest part of the coil will be deformed, resulting in the formation of cracks in the tubes.

In order to obtain a higher air temperature the Industrikemiska Aktiebolaget in Stockholm developed a new superheater (INKA) for air, gas, or steam, consisting of vertically (or nearly vertically) arranged straight tubes for super-

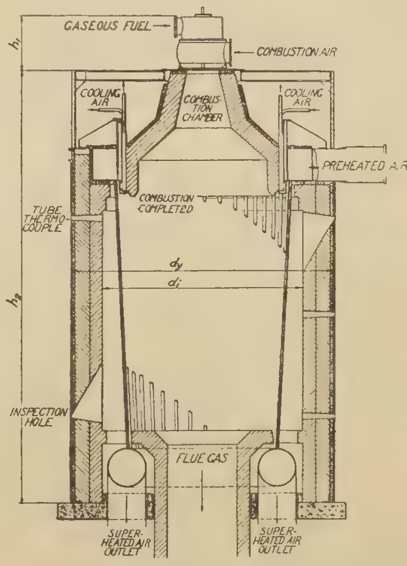


FIG. 8.—INKA Air-Preheater.

h_1.		h_2.		d_i.		d_y.		Capacity.	Air Temp.
Ft.	In.	Ft.	In.	Ft.	In.	Ft.	In.	Cu.ft./hr.	° F.
5	0	37	0	14	10	16	8	650,000	1470
4	0	24	6	12	6	14	10	285,000	1470

heating the air (*see* Fig. 8). The tubes are fed from a ring main and discharged into a circular

collecting-tube, the latter being connected to the service main.

The apparatus is heated by hot waste gases or, as is shown in Fig. 8, by means of a gas-burner, which is specially built for the purpose of obtaining a very rapid combustion of the fuel gas.

The very hot gas (*e.g.*, up to 3500° F. (1930° C.)) from the combustion chamber radiates part of its heat content to the vertical tubes. The hot-gas flow is, as far as possible, brought parallel to the vertical tubes and descends through the centre of the apparatus; hence the heating surface is very well protected against dust deposition and from the hot-gas flow. In fact, the heat transmission is normally effected to about 95–97% of its potential by radiation—and this is essential; the absence of convective heat transmission diminishes the danger of local superheating of the tube material and, likewise, the deposition of dust.

This apparatus, working with parallel flow which makes possible the attainment of a very uniform and very high tube temperature (up to 1700° F. (930° C.) over the entire length of the tubes, allows the procurement of a high heat transmission—up to about 10,000 B.Th.U./sq.ft. (27,000 kg.cal./sq.m.) of tube surface per hour.

To obtain a high thermal efficiency the heat of the flue gas from this apparatus must be utilized, preferably in an air-preheater—built on principles of convection—from which the preheated air at temperatures of about 750° F. (400° C.) can enter the INKA and be superheated there to the temperature desired. To-day, air temperatures of 1500° F. (800° C.) are regularly being maintained by such apparatus in practice. This heating system allows a high degree of thermal efficiency to be attained and will probably be adapted for use at the blast-furnaces, in combination with the Lindblom air-preheater already described.

It ought to be mentioned that by the autumn of this year an INKA designed for the superheating of steam up to a temperature of 1830° F. (1000° C.) will be available.

Both types of air-preheaters described have also been used as recuperators for the reheating furnaces at the steelworks. In this connection another new piece of plant, the so-called fan preheater (made by A/B. Motalla Verkstad in Sweden), should be mentioned; this apparatus will be described later in the present paper.

To return to the use of blast-furnace gas, in Sweden, as in most other countries, the surplus gas is usually used for heating purposes. At some places it is mixed with producer gas or with electric blast-furnace gas and used in the reheating furnaces at the rolling mills. In other cases it is used mainly for the raising of steam.

Electric Pig-Iron Furnaces and Sponge-Iron Processes.

In countries where electric power is cheap in comparison with blast-furnace coke, the electric pig-iron furnace has a definite place. The type mostly used in Sweden is the shaft furnace called the Electro-metals furnace, constructed by Messrs. Grönwall, Stålhane, and Lindblad; this furnace has been adequately described in the technical literature.* The Electro-metals furnace, however, has two disadvantages: It is not possible to build it in larger units than for a production of about 50 tons per day, and it cannot be operated with coke exclusively as the reducing agent. If certain limits in both these respects are exceeded, risks of explosions ensue.

During and shortly before the war some electric

TABLE II.—*Consumption of, and Costs for, Fuel and Electric Energy for Different Methods of Reduction of Sintered Rich Iron-Ore Concentrates.*

Price of Material.	Pig Iron.								Sponge Iron (Wiberg).			
	Blast Furnace.				Electric Furnace.							
	Charcoal Pig Iron.		Coke Pig Iron.		Electro-metals Furnace.		Tysland-Hole Furnace.		Charcoal.		Coke.	
	cwt./ton.	Kr./ton.	cwt./ton.	Kr./ton.	cwt./ton.	Kr./ton.	cwt./ton.	Kr./ton.	cwt./ton.	Kr./ton.	cwt./ton.	Kr./ton.
Charcoal: Kr.88/ton (Kr.1·50/hl.†)	14	61.00	...	...	7·7	34.00	...	...	5·3	24.00	...	...
Coke: Kr.40/ton	...	...	14	28.00	...	...	4·00	8.00	...	...	4·0	8.00
Coke breeze: Kr.30/ton	...	...	...	...	...	...	4·00	6.00	...	...	...	...
Electric power: Kr.0·01/kWh.	...	...	...	...	2,200 kWh.	22.00	2,500 kWh.	25.00	860 kWh.	8.60	860 kWh.	8.60
Electrodes: Kr.0·14/lb.	...	...	...	...	13 lb.	1.80	27 lb.	3.70	9 lb.	1.20	9 lb.	1.20
Total: Kr.	...	61.00	...	28.00	...	57.80	...	42.70	...	33.80	...	17.80
Credit for blast-furnace gas	...	5.00	...	5.00	...	6.00	...	6.00	...	...	...	...
Total: Kr.	...	56.00	...	23.00	...	51.80	...	36.70	...	33.80	...	17.80

† Hectolitre.

* *See*, for instance, Clements, "Blast-Furnace Practice," vol. 3, p. 382. London, 1929: Ernest Benn, Ltd.

furnaces of the Tysland-Hole type were built in Sweden. This furnace was invented and developed in Norway (at Kristiana Spigerverk) and is now marketed by Norsk Elektrokemisk A/S. It is a low shaft furnace with three vertical electrodes (mostly of the continuous Söderberg type), and was described by Hole,* by Hole and Willners,† and by Cowes.‡ This type of furnace can be operated with coke as fuel. Hitherto the Tysland-Hole furnace has not been built for a greater production than 125 tons per day, but much larger furnaces of this type are now being constructed. A great advantage of the furnace is that up to 50% of the fuel used can consist of coke breeze; on the other hand, the fuel consumption and also the power consumption are somewhat higher than for the Electro-metals furnaces.

Fuel and power consumptions and costs for the different methods of reducing rich sintered concentrates (including the Wiberg sponge-iron process) are given in Table II.; the price levels chosen correspond to future hopes, but, as the price of fuel may be higher than anticipated, the assumed total fuel costs for iron production have also been calculated, the assumptions used being that the price of fuel and electrodes will be 50% higher than the corresponding figures in Table II., but that electric power will still be obtainable at the price there quoted (Kr.0·01/kWh.), which will be the case for several years to come, in Northern Sweden at least. The assumed total fuel costs are:

	Price per Ton of Product, Kr.
Blast-Furnace Pig Iron.	
Charcoal	84.00
Coke	34.50
Electric-Furnace Pig Iron.	
Electro-metals furnace (charcoal)	66.70
Tysland-Hole furnace (coke)	51.60
Sponge Iron (Wiberg).	
Charcoal	46.40
Coke	22.40

On both the assumptions mentioned it is evident that the sponge-iron process (when coke is used) will be the most economical method. The costs given for this product are calculated on the iron content.

In comparing the sponge-iron process with the pig-iron process it should always be borne in mind that the melting and refining costs must be higher with sponge iron than with pig iron, especially when the latter is brought to the refining furnaces in a molten condition.

A full-sized Wiberg furnace has been working continuously for the past four years at Söderfors, with excellent results. The furnace belongs to Stora Kopparbergs Bergslags A/B., who have made a great contribution to the development of this process. Until now the only fuel used has been charcoal but, at the time of writing, experiments are about to start with coke as the reducing agent; the results of these experiments should be of the utmost interest. A description of the Wiberg process and the results obtained at Söderfors have been published in a very interesting paper by Améen.§

A new method, also introduced by Wiberg, must be mentioned in this connection; in the near future, at the new Government-owned plant at Luleå, experiments in the use of pre-reduced ore will be started in the Tysland-Hole furnace. The gas from the furnace will be used for the pre-reduction of the sintered ore in a shaft furnace similar to the Wiberg sponge-iron furnace. In this way it seems possible to reduce the consumption of fuel and power by 20–30%, which will quite appreciably diminish the fuel and power costs of the electric pig-iron process. In using rich ores it might be advantageous to smelt the pre-reduced ore with charcoal or coke in an electric steel furnace, thereby producing steel directly instead of pig iron.

The Höganäs sponge-iron process, which has been in continuous operation in Sweden since 1911, is also of great interest. This method has three advantages: (i) Coke breeze or low-grade coal can be used as the reducing agent and fuel; (ii) it is not necessary to sinter the concentrates before use; (iii) the product obtained will be very pure, as no sulphur or any other contamination will occur during the process.

The disadvantages of the process are a high consumption of refractory material and higher building and labour costs than those for the Wiberg process. It is of great advantage to use the richest concentrates possible as raw material for the sponge-iron processes, as a high content of gangue in the sponge iron will result in higher melting costs in the steel furnaces. A description of the history and present state of development of the Höganäs process has been given by Eketorp.||

Open-Hearth Furnaces, Gas Producers, and Reheating Furnaces.

In the gas producers for the open-hearth furnaces it was generally not difficult to turn to wood as fuel. Provided that dry wood is obtainable and that the grate area of the gas producer is sufficient, there need be no difficulties

* *Jernkontorets Annaler*, 1937, vol. 121, p. 667.
† *Teknisk Tidskrift*, 1939, vol. 69, (Feb. 11), Bergvetenskap No. 2, pp. 9, 11.
‡ *Iron Age*, 1942, vol. 150, (Dec. 3), p. 41; (Dec. 10), p. 50.
§ *Jernkontorets Annaler*, 1943, vol. 127, p. 277.
|| *Jernkontorets Annaler*, 1945, vol. 129, pp. 703–721.

in maintaining production at the open-hearth furnaces. In some cases equipment for drying the wood by means of waste gases from the open-hearth furnaces was installed and, naturally,

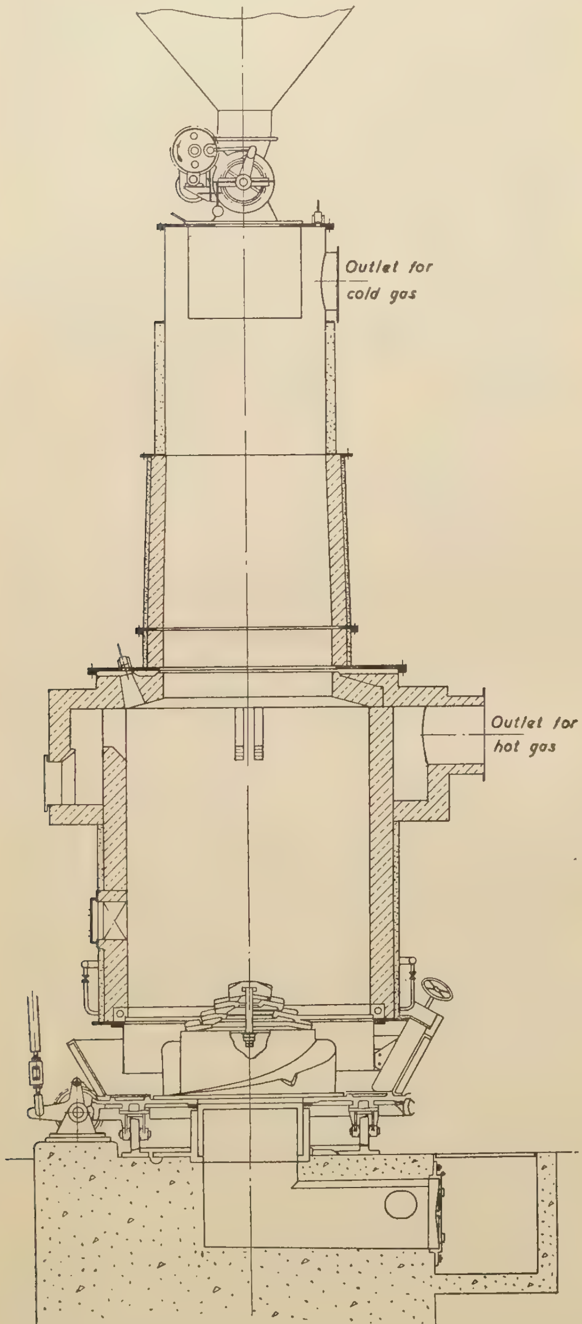


Fig. 9.—Gas Producer with Two Gas Outlets.

new arrangements had to be made for the transport and the charging of this much more voluminous fuel.

Large installations also had to be made for cutting the wood into small pieces suitable for use in the gas producers; a size corresponding to that of an ordinary match-box was found to be satisfactory.

To a small extent, peat has also been used in the gas producers for the open-hearth furnaces, with good results. The scarcity of coal and the high prices of wood and peat have forced upon the Swedish open-hearth operators the vital necessity of reducing fuel consumption; in this they have succeeded, attaining coal consumptions as low as approximately 3·5 cwt./ton (170–180 kg./metric ton) in 25–45-ton furnaces, using cold charges. To achieve such results, great care has to be taken in the control of the furnaces.

At some plants the open-hearth furnaces are charged partly with molten pig iron and, at others, preblown Bessemer steel is used. Naturally, both these methods increase the production of the open-hearth furnace and reduce the fuel consumption.

Waste-heat boilers for utilizing the heat in the waste gases from the open-hearth furnaces have been installed at one or two plants. Were coal prices lower, the building of waste-heat boilers in connection with open-hearth furnaces would scarcely be considered, because of the heavy erection costs; the subsequent price of steam would be too high. Waste-heat boilers are generally more economical when installed behind heating furnaces where the stack gases leave the furnace at a high temperature. In many other cases it has been found more economical to use air-preheaters, whereby a direct reduction of fuel consumption for the furnace itself is obtained.

With regard to the heating of ingots and billets for the rolling mills, at some Swedish works hot stripping of the ingots is employed, as well as soaking pits. In the production of quality steel this method is not possible, as the ingots must be inspected and, very often, conditioned before rolling.

For the heating of billets and ingots, gas-fired furnaces are used more frequently, and at some works central gas-producing plants have been built. In this field a new construction, the principles of which are shown in Fig. 9, has been tried. In this producer, when working with good coal, about 40% of the gas is passed through the upper part of the shaft, while the remainder is taken out at the lower level. The latter gas has about the same composition as ordinary producer gas made from coke, and it leaves the producer at a temperature of 1110° F. (600° C.), while the gas coming from the upper outlet is very rich, containing as it does all the distillation products from the coal; this gas leaves the gas producer at about 190° F. (90° C.) and is conducted through an electric gas-cleaning filter, where the tar is completely removed. The gas from the lower outlet is led only through a dust-

catcher, and finally both gases are mixed. The upper gas has a heat value of 180 B.Th.U./cu.ft. (1620 cal./cu.m.) and the lower gas a value of about 150 B.Th.U./cu.ft. (1350 cal./cu.m.). The mixture will have a heat value of about 165 B.Th.U./cu.ft. (1480 cal./cu.m.).

The yield of tar generally amounts to about 8% of the coal charged, and its quality is much higher than that of ordinary tar from gas producers; its viscosity being about the same as that of fuel-oil, this tar may very well be used for many heating purposes.

Experiments with this type of gas producer were originally carried out at the works of Höganäs-Billesholms A/B., and its use at steel plants has been brought forward at Degerfors. The producer was placed on the market by A/B. Motala Verkstad, who have also contributed to the development of this construction.

In the steelworks there are great advantages to be obtained from the centralization of the gas producers in relation to the furnaces, and from the use of a rich, clean gas. With centralization of the producers the transport of coal and ash from the different units is expedited. With clean gas no soot or tar is deposited in the gas tubes or burners, and the furnaces can be fired very regularly with the exact admixture of air necessary; perfectly smokeless combustion can be maintained, and the works can easily be kept very clean and tidy. Consequent upon the greater possibilities of exactly controlling the furnaces, a direct saving of fuel is also obtained.

A new type of stoker, developed from an originally French type made by Svenska Järnvägsverkstäderna at Linköping, is now competing with the centralized gas-producer system just described. This stoker was reconstructed for the use of wood by Nils Ericsson (at Bofors), who has developed and described * the apparatus. At Bofors the stoker is operated in such a way that a hot producer gas is obtained, the gas being conducted into the furnace through burners made from refractory material; the construction of the stoker and of the hot-gas burner is shown in Fig. 10. The stoker-fired furnaces can also be much better controlled than directly fired furnaces. The automatic feeding makes it possible to use very large fuel hoppers over the stoker screws. At Bofors the coal is transported to the different units by endless belts running under the roofs of the buildings. A very high thermal efficiency can be obtained in stoker-fired furnaces, and no losses in tar, soot, or physical heat occur.

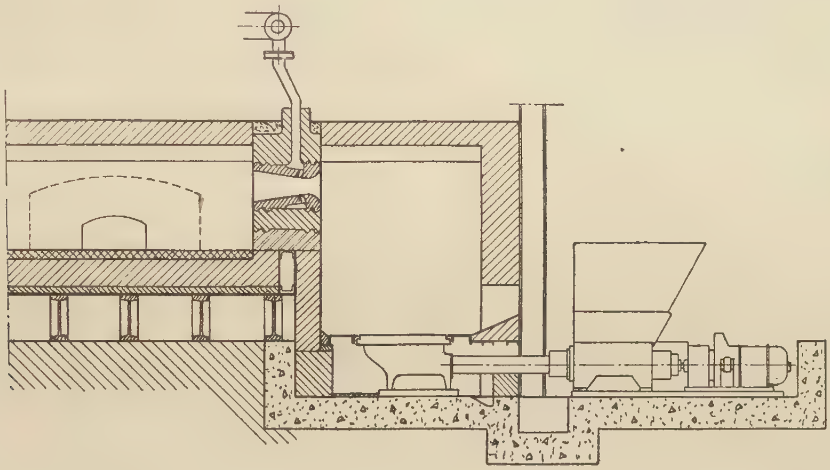


FIG. 10.—Stoker-Fired Reheating Furnace with Hot-Gas Burner.

During the war practically all of the heating furnaces in Sweden were provided with air-preheaters, generally of the Lindblom type already mentioned, though other types of steel recuperators were also installed.

A quite new type of air-preheater, called the fan preheater, has been constructed by Vannérus at A/B. Motala Verkstad. The construction of this preheater is rather complicated, and perhaps the illustration (Fig. 11) will not give a clear view of it. The heating surface of the fan preheater consists of a number of annular plates placed at right angles to the shaft. The plates are so arranged that the air coming in at one end of the rotor passes through every alternate spacing between the plates, the gas which comes in at the opposite end of the rotor passing through the other alternate spacings; each plate is thus in contact on one side with air and on the other with flue gas. The plates being placed at right angles to the rotating shaft, a high velocity in relation to the lagging air and gas is imparted to them and, because of these circumstances, an excep-

* *Jernkontorets Annaler*, 1944, vol. 128, p. 29.

tionally high transmission of heat is obtained. Simultaneously, the air- and gas-carrying action

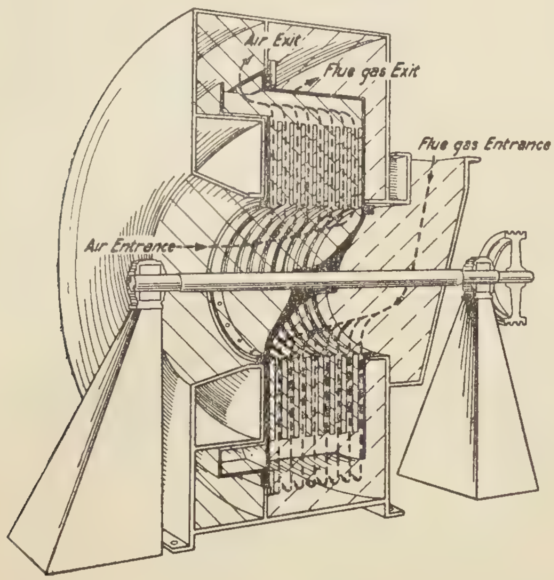


FIG. 11.—The Motala Fan Preheater.

of the plates (arising through the motion friction) is converted into useful fan work. This preheater has, so far, been used up to temperatures of only 750° F. (400° C.), but apparatus for higher temperatures are being constructed. A great advantage of the fan preheater is that it combines in a single compact machine an air-preheater with a waste-gas fan and a fan for preheated combustion air. On account of their great velocity the heating surfaces are not covered with soot, and thus a good transmission of heat is facilitated. The construction has frequently been used for preheating air for steam boilers, and also for heating furnaces.

III.—Future Prospects of the Swedish Iron and Steel Industry.

In a country like Sweden, where the cost of fuel must always be high in comparison with that in large iron-producing countries, it is essential that everything possible be done to keep the fuel consumption down to a minimum; in this respect lessons have been learned during the war which will be of the greatest importance in the future. The necessity of fuel economy has long been realized by Swedish metallurgists, but the conditions experienced during the war made it clearer than ever that the predominant factor in the very existence of the native iron and steel industry will be the fuel problem. It is obvious that the radical changes in equipment and methods that have been necessary in the Swedish iron and steel industry during the war must inspire and accelerate plans for the future development of that industry. As mentioned before, the natural advantages possessed by Sweden consist of the large resources of pure iron ore, which can be concentrated into a product containing nearly 100% of iron oxides, and of the relatively great supplies of hydro-electric power available; special methods must be applied to utilize these advantages to the full.

With regard to the production of quality steel, it may well be a question of a relatively short time before it will be economically impossible to use charcoal as a fuel for the production of pig iron.

The personal opinion of the author is that within a few years many quality-steel works will change partly or completely from charcoal pig iron to sponge iron as a basis for their production. To-day, very interesting and comprehensive experiments are being made to find the best methods for using a high percentage of sponge iron in the acid open-hearth furnaces. In the electric steel furnaces the problem has already been solved and at Söderfors, where the steel is exclusively made in electric furnaces, the basis for the production is 100% sponge iron.

The " trend curves " for the production and consumption of steel in Sweden show that, within 15 or 20 years, the country ought to be self-supporting in commercial steel also. This would mean quite a rapid development of the commercial steel works, and it is of great importance that the right methods should be used in extensions of existing plants and at the new plants necessary.

Swedish metallurgists believe that sponge-iron methods would hardly be economical for the production of commercial steel, and it is most likely that more coke blast furnaces will be built. As mentioned before, the fuel consumption in these furnaces can be kept very low if rich sintered concentrates are used exclusively.

If the world market price of scrap should decrease in relation to the price of pig iron, the basic open-hearth process will naturally justify its position, even to a larger extent than it does to-day. The methods used in England, where open-hearth furnaces are run with a high percentage of molten pig iron, will hardly be utilized in Sweden. Most likely, a considerable part of the future Swedish commercial steel production will come from Thomas and Bessemer furnaces.

The " R.K." process for the production of decarburized granulated pig iron, invented by Kalling and Rennerfelt,* has been tried at several

* See *Journal of The Iron and Steel Institute*, 1939, No. II., p. 137 P.

works during the war, with very good results. At one plant "R.K." furnaces designed for an annual production of 75,000 tons will be installed, and at many places the "R.K." furnaces will no doubt compete with Thomas and Bessemer furnaces.

Many electric steel furnaces, also for the production of commercial steels of high quality, are planned or are already being built in Swedish steel plants; this type of furnace has been found to be very useful for refining liquid Thomas or Bessemer steels.

Throughout the war a great deal of work has been done in the modernization of the Swedish steel plants. Several new rolling mills have been built or are in process of building and special stress has been laid upon the modernization of transport arrangements in the plants.

Much effort has also been spent on the development and control of steel quality. A large number of new laboratories have been built, and co-operative research never flourished so much, nor showed itself so useful, as it did during this last world war. We have good hopes for the future in every respect.

[This paper was discussed jointly with the following two by C. Hulse and R. J. Sarjant on "Problems in Fuel Efficiency" and by N. H. Turner and F. A. Gray on "Fuel Utilization in Iron and Steel Works."]

PROBLEMS IN FUEL EFFICIENCY.*

By C. HULSE, B.Sc., and R. J. SARJANT, D.Sc. (Messrs. Hadfields, Ltd., Sheffield).

Synopsis.

Problems in fuel efficiency relating to works where processes may be specialized are discussed in relation to the bearing of fuel selection on efficiency, developments in furnace design and construction, methods of fuel saving in individual works, education, and research. The present position is reviewed and lines of future development are suggested.

I.—Introduction.

The objects of this paper are to review the present position of some of the problems relating to the efficient use of fuel in the iron and steel industry, and to indicate possible solutions and lines of approach for future developments.

In many respects the present position in regard to post-war coal utilization includes features which are a repetition of the situation existing at the end of the 1914–1918 War. Then, as now, there was a rude awakening to the necessity for the conservation of the fuel resources of the country, and steps were undertaken to remedy the state of affairs. The setting-up of the Fuel Research Board and, through that body, the undertaking of scientific surveys of the coalfields and of industrial developments were among the measures embarked upon; the survey of industry was the occasion for the first systematic investigation into the question of fuel economy on an industrial scale. At the same time an impetus was given to the scientific study of plant design, a statement which may give rise to controversy. One of the authors made his first acquaintance with the iron and steel industry as a result of the campaign then waged.

The question of coal utilization has come to the fore yet again, not solely as a question of conservation but rather as a matter of the sheer necessity of making existing supplies go round. Yet again has the admonition been raised that there is a crying need for the application of existing knowledge, rather than for the further elucidation of the scientific principles involved; this was the plea made by W. A. Bone, an earnest advocate of conservation in the former campaign. Again the technical resources of the country have been mobilized with the object of obtaining the more efficient use of fuel, and the question now arises as to how the lessons learned during the war can be utilized to ensure not only that no further danger of lack of supplies can arise, but also that the object of conservation may be fully attained. A serious economic feature now also presents itself, namely, the important part that indigenous fuel must play in the nation's struggle for export trade.

The problems discussed in this paper relate to works where processes may be somewhat specialized and where there has been in the past a free selection of the most suitable fuel for a specific purpose, according to its availability and economy of utilization. They do not necessarily apply to works of the fully integrated type, where the sole use of coal is limited to the coke ovens and where the secondary needs for heat and power are satisfied by the available supplies of by-product (blast-furnace and coke-oven) gases.

For the purposes of this presentation, the problems may be classified as follows: (i) Those dealing essentially with the fuel and the means taken for its efficient combustion; (ii) those relating to plant design and the mode of heat transference to the medium being heated; (iii) those mainly associated either with organization or with technique. In this last section special prominence is given to the need for plant surveys with suitable instruments, and for the necessary organization and education to ensure the application of existing knowledge among the many, rather than to rely on spectacular advances by a few. Finally, some of the wider problems of research involved are briefly considered from the angle of suggestion.

II.—The Bearing of Fuel Selection on Efficiency.

Much controversy has raged round the question of the price structures of fuel for different purposes; this problem stands out as a national one and demands the earliest possible attention. Availability of any type of fuel is mainly a local question, and little can be done in the present circumstances of restricted supply to obtain the ideal fuel for a specific purpose. Many works had during the years before the war worked out their own

* Received February 11, 1946.

salvation in this respect, but war conditions have since interrupted such selection to a considerable extent. The works with which the authors are associated had for many years utilized a method of evaluating coals for industrial uses on a thermal basis, in which the ascertained calorific value on a basis of unit cost was adjusted for various operational factors; the result was that an "industrial value" of the fuel was determined. In the case of coal these factors had reference to ash content, clinkering characteristics of ash, and swelling character, while in the case of coke much importance was attached to the significance of the drop test, which had been found to give the best criterion of a hot-melting coke for cupola practice. In recent years, however, the problem has been to apply a much wider range of fuels (usually of an inferior character) to uses to which a particular selected fuel had previously been applied. How far it is desirable in the national interest and on technical grounds to revert to a free selection of suitable fuel is a point which might well be given consideration.

Coal.

Coal is still the cheapest available source of heat for industrial purposes and probably will remain so for many years to come. In furnace practice, however, the cost of the heat unit must be considered, not at the point at which the fuel is burned but where it enters the material being heated. In this respect the questions of thermal efficiency, ease of control, labour, maintenance, and transport of fuel and ash require to be considered. When these factors are taken into account the pre-eminent position of raw coal becomes seriously challenged by gaseous fuels and even, in some cases, by electricity. These challenges become all the more real when the questions of quality of heating and of convenience of operation are considered.

In certain cases (*e.g.*, a furnace used only at infrequent intervals) economic considerations may actually favour the continuance of a wasteful method of firing on the grounds that further capital expenditure is unjustified; even where the situation would warrant replacement by a more modern unit other factors might delay the change-over. The cautious industrialist cannot be blamed in these days if he elects to continue with the use of a fuel of which he has been receiving reasonably regular supplies, rather than tie up his capital in plant requiring a grade of fuel which might later prove difficult or impossible to obtain. Such conditions have favoured the retention of the practice of hand-firing on grates.

Hand-Firing on Grates.

The greatest disadvantage of this type of firing, compared with other means, lies in the lack of control over combustion. At a given rate of input of primary air the secondary-air requirements vary continuously during each firing period, resulting in wide variations in the composition of the furnace atmosphere. This is not only wasteful in fuel but, in certain types of operations (particularly at high temperatures or if the sulphur content of the coal is high) the variations may lead to heavy scaling of the charge. As has been shown by various workers,[1, 2, 3] the degree of scaling increases rapidly with increasing oxygen

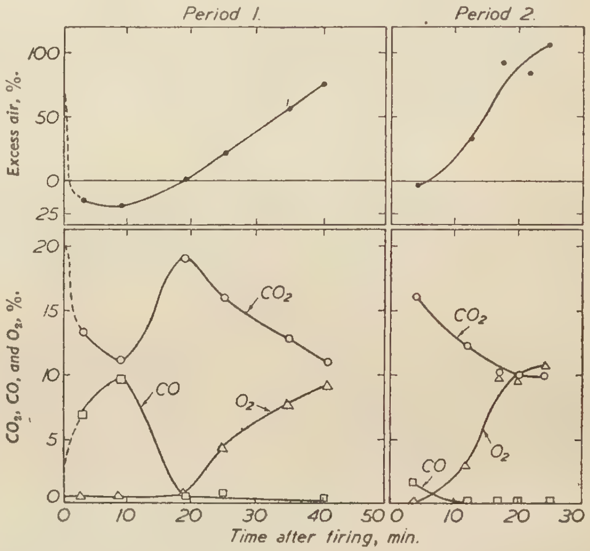


FIG. 1.—Variations in Composition of Furnace Atmosphere of Hand-Fired Furnace. (Periods 1 and 2 relate respectively to firing periods during the early and latter stages of heating-up from cold.)

content of the furnace gases, and considerable scaling may be produced by sulphur dioxide, even in reducing atmospheres.

A further complication with which the operator of a hand-fired furnace has to contend is that as the furnace temperature rises the draught at the stack increases. This applies equally to all types of natural-draught furnaces, but when this variable is added to the cyclic variations of each firing period, the task of maintaining constant combustion conditions becomes well-nigh impracticable for modern standards of heating requirements. By proper attention to the design of the combustion chamber and by using one of the proved methods of firing (combined with good firing technique) it is possible to achieve a certain degree of uniformity, but even under the best conditions quite serious variations may occur.

An illustration of the type of result which may be expected when conditions are not of the best is given in Fig. 1. This shows the variations in composition of the furnace gases observed throughout two firing periods during the heating from cold of a batch-type heat-treatment furnace.

The first set of curves relate to a period during the initial stages of the heat, when the furnace and charge were still relatively cold, and the second to a period when the furnace was nearly up to temperature. It will be seen that wide variations occur in both cases, the conditions ranging from strongly reducing to strongly oxidizing. Thus, the extreme values recorded in the first set of curves were, on the one hand, nearly 10% of CO and, on the other hand, 9% of oxygen, the latter corresponding to about 76% excess air. Comparison of the two sets of curves reveals that the point in the cycle corresponding to 25 min. after firing in period 1 is reached in the case of the second period in only 4 min., and that the rate of increase in the excess air is much more rapid in the second case. As the rate of supply of primary air was similar in the two cases (if anything being slightly less in the second) it is apparent that, apart from any slight differences in the conditions of the fuel bed, in period 2 the duration of the evolution of the volatile matter was much shorter, owing to the higher temperature of the firebox and furnace generally, and the amount of secondary air drawn into the furnace was much greater, also because of the higher temperature of the furnace system.

Firebar Design.

As it would appear that hand-firing must remain as a practical technique for some time yet, the problem of grate design, particularly of the bars, still remains; the authors consider that finality has not yet been reached in this question. Little is known of the laws governing the conditions of flow inside a bed of burning coal, and present grate designs are largely based on trial and error. In the case of one particular design and for the same type of coal it was found that an expression of the type:

$$P = cF^n$$

where P = pressure drop (in. W.G.),
F = air flow (cu. ft./min./sq. ft. of grate area),
and n and c are constants,

gave a partial correlation. When P and F were plotted logarithmically all the points fell on a band which gave a value for n of approximately 1·45, the position in the band being apparently dependent upon the time after firing. There would seem to be a case for further work along these lines, including additional factors, such as the type and size of coal and the depth of the bed.

Mechanical Stoking.

Most of the disadvantages associated with the firing of raw coal are mitigated by the use of mechanical stoking. As the fuel is fed continuously into the combustion chamber, the primary and secondary air are both capable of correct adjustment and may be made to follow variations in the rate of fuel feed as governed by the load requirements. The readiness with which mechanical-stoking appliances may be adapted to automatic control is a further point in their favour.

Table I.—*Combustion Conditions in Stoker-Fired Furnace.*

Furnace Conditions.	Furnace Atmosphere.				
	Composition, %.			Air.	Volatile Unburnt Combustibles, %.
	CO_2.	O_2.	CO.		
Heating-up cold charge; smoky flame	18·3	0·8	0·1	Negligible excess.	0·4
Heating-up cold charge; flame more smoky	18·1	0·3	1·5	Slight deficiency.	5·1
Soaking heat; slightly smoky flame	18·3	0·7	0·6	Negligible excess.	2·1

Typical combustion conditions which were obtained during tests at two similar rolling-mill reheating furnaces, one fitted with an underfeed-type mechanical stoker and the other hand-fired, are contrasted in Tables I. and II.

Table II.—*Combustion Conditions in Hand-Fired Furnace.*

Furnace Conditions.	Air.
Average; immediately after firing.	Deficiency to 20% excess.
After raking fires during period when flame was coming over the bridge.	60–80% excess.
During periods when the fire had burned down and the furnace chamber was clear.	100–150% excess.

The bearing of such differences as those illustrated in Tables I. and II. on the question of fuel economy, as well as on that of loss of steel due to scaling, will be readily appreciated. Nevertheless, in spite of the advantages shown in these tables to be possessed by mechanical firing, and keeping in mind the other obvious superiorities of this system, there is still considerable room for improvement both in the design and the performance of mechanical-firing appliances. The demands made by metallurgical furnaces are much more stringent than those encountered in

boiler practice, in which field the technique of mechanical stoking found its first ready success. Considerable flexibility is required, and sometimes load conditions may render desirable the reduction of the rate of fuel feed below that at which burning-back of the fuel, or damage to mechanical parts owing to radiation from the combustion-chamber refractories, may take place. Another point in this connection is that combustion-chamber temperatures are necessarily higher in furnace practice than in boiler practice for the same size of stoker. In such cases the costs, either of fuel or of maintenance, are bound to be higher than is desirable.

In many existing installations economy could probably be effected by attention to points of detail. This was exemplified in a recent test of the rolling-mill furnace already mentioned in connection with Table I., in which it was found that, although at suitable rates of output a fuel consumption of less than 2 cwt. per ton of product was attained, the degree to which the rate of fuel feed could be varied was insufficient to meet all types of demand. In actual fact only three rates of fuel input were possible, amounting to 35, 60, and 100% of the full load. In such cases as this considerable savings may be achieved by small mechanical modifications of the controls to give greater flexibility, and by ensuring that the air-valve settings corresponding to the different rates of fuel feed are clearly marked and properly set.

Pulverized Fuel.

Up to the commencement of the war great strides had been made in the use of pulverized coal for furnace firing. The modern remote-control bin-and-feeder system and unit pulverizers are both capable of giving a degree of flexibility of control which approaches that attainable by the use of gaseous fuels, and the more recent designs of pulverizing equipment have achieved a standard of reliability in providing a product of uniform fineness adequate for most furnace purposes. As with gaseous fuels the burners may be disposed in a manner designed to give as rapid a rate of heating as is consistent with the limitations imposed by the nature of the material to be heated, and to assist in the ready attainment of temperature uniformity.

On the other hand pulverized-fuel installations necessitate both careful design and subsequent rigid control if the troubles associated with their use are to be avoided. The worst of these troubles is probably that of fluctuations in the rate of fuel feed. These may be due to irregularities in the pipe-lines or to too high a moisture content in the coal, and may lead to actual blockage. For this reason it is essential that the moisture content of the coal going to the pulverizers should be kept below a very low upper limit, and it may be necessary to instal some form of coal drier. High rates of output and efficiency are obtainable even with coals of high ash content; indeed, the use of pulverized coal as a boiler fuel was originally adopted partly with a view to the utilization of low-grade fuels. The marked progress in American pulverized-fuel practice can be ascribed to the existence of a relatively high ash content in many American coals. In furnace practice it is usually desirable to keep the ash content as low as possible as, even with moderate ash contents, flue deposits build up all too quickly, and it is inevitable that finely divided coal ash should become a strong fluxing agent on brickwork, particularly at high temperatures. The authors have experienced cases in which the ash from powdered coal has been sintered solid in the off-take flues, owing to irregular combustion conditions arising from choking of the feed mains and the resulting fluctuations in the rate of coal feed. It is owing to the fine ash carried over by the waste gases that waste-heat recovery is not generally practised in conjunction with powdered-coal firing, and the practical difficulties to be overcome in this connection are most formidable. A further problem in connection with this method of firing, particularly in the case of large installations, is that of atmospheric pollution from the emission of grit, the prevention of which demands auxiliary grit-arresting plant.

Coke.

Were it not for the fact that the price per therm compares so unfavourably with that of coal, the use of coke for furnace heating would be even more widespread than is the case at present. As coke consists essentially of carbon (together with impurities in the form of ash) the disabilities associated with the cyclic variations in the secondary-air requirements in the case of coal do not apply. Provided that the grates are maintained in good condition and a firing system is adopted which will maintain a uniform fire, good control of combustion conditions and of the composition of the furnace atmosphere is practicable.

Coke is widely used in foundry practice of all kinds, though even in this application it is to-day being replaced to some extent by gaseous fuels. For many years it has found a ready application in built-in producers (by means of which the sensible heat in the producer gas may be utilized) and in suction units used primarily for power production by means of gas engines. More recently, however, there has been a marked trend for the submission of coke to gasification in centrally situated units. These units are usually associated with a wet-cleaning plant, and the cleaned gas is boosted to a pressure of about 2 lb./sq. in. for distribution.

Gaseous Fuels.

Clean gaseous fuels are almost ideal in respect of ease of control of combustion, the degree to which the type and nature of the flame may be varied, and the readiness with which they lend themselves to automatic control. These and other features, together with the fact that burners of suitable type may be placed in such positions with respect to the charge as will enable rapid and uniform heating to be obtained, give the furnace designer greater scope in the matter of mechanization, waste-heat recovery, and the use of special designs to suit particular requirements. It is significant that most (if not all) of the more fundamental changes in furnace design which have taken place in recent years have been associated with the use of gaseous fuels or of electricity.

By means of equipment of a special type, utilizing the principle of surface combustion, exceedingly high rates of heat release may be obtained and there would seem to be scope in this country for the more extensive use of this form of heating, which in America is now finding increasing application, with almost phenomenal results.

In regard to rates of heating in furnaces, experience with the type of burner mentioned has shown that much higher rates of heating are practicable with metals than had hitherto been thought to be the case. This has been shown also by a recent paper,[4] in which it was demonstrated that the practicable rates of heating of steel (in so far as no disturbing metallurgical requirement may limit those rates) are higher than had been realized, provided that the heating is uniform on all sides of the material being heated; this last circumstance determines in many cases the heating times required. In practice it would appear that the principal factor governing the soaking time required to attain temperature uniformity is the limitation imposed by the furnace, and particularly by a cold hearth, and not the thermal characteristics of the material being heated. In so far as progress may be made towards overcoming the disabilities indicated, the use of either gas or electricity, preferably in combination with mechanisms which may move the charge, would appear to be necessary.

A modern means of attaining better uniformity of temperature in a furnace chamber is the use of the so-called diffusion burner, in which the gas and air are projected into the furnace in a number of parallel streams which slowly diffuse and give a long flame. Another method of obtaining slow admixture of gas and air was applied in the Chantraine furnace; this type of furnace has been in use for many years. In this case the gas is admitted to the furnace chamber either through a port at the end of the furnace or at a number of points along its length, at a level just above the hearth; the object of the latter modification is to reduce the incidence of scaling by the provision of a rich gas in proximity to the charge. The air is admitted through a series of ports in a false crown. Success in attaining the objects sought has been claimed both for the diffusion burner and the Chantraine furnace.

Fundamental research into the combustion of inflammable gases in both aerated and non-aerated burners has been undertaken by Professor D. T. A. Townend and his colleagues at Leeds University. The work so far published [5,6] has been concerned with the measurement of flame velocity and the mechanism of the phenomena of light-back and blow-off. In light-back the gas velocity at points nearest the periphery of the burner throat, and the character of the dead space, would appear to be of importance. In aerated flames the tendency for the flame to blow off decreases as the burner diameter increases, and double-cone flames are progressively more stable as the proportion of the gas in the mixture is increased. The publication of the results of further work along these lines, which work should be capable of putting burner design on a scientific footing, will be awaited with interest.

The national position with regard to coking coals gives one furiously to think how the problem may be approached from the standpoint of the industrial user of gaseous fuel in the future. Undoubtedly the gas industry may be able to help by extending the range of coals which may be economically gasified in retorts; also it may be necessary to practise total gasification on a larger scale than at present. In this connection the question of water supply for cleaning the gas and for the subsequent removal of undesirable impurities from the effluent offers a problem of some magnitude; the alternative use of electrostatic cleaning provides a promising future line of approach to this question. A further distribution problem is associated with the high pressures and the large-diameter pipes required to distribute gases of low calorific value. In certain circumstances, depending largely on economic considerations relating to the size of the units, it may be necessary to locate the production unit adjacent to the works. On the other hand the case may be cited [7] of the use of Mond gas in South Staffordshire, where gas of a calorific value of 160 B.Th.U./cu. ft. is supplied at a distribution pressure of 7 lb./sq. in. to works scattered over an area of approximately 100 sq. miles; this system has now been operating for many years.

Coke Producer Gas.

Mention has already been made of coke producer gas; in specific uses this forms a practicable substitute for town's gas, over which it has some advantage in the heating of metals in respect of its

low flame intensity. The following information relates to the cleaning and purification of coke producer gas in the case of two recently installed plants with a total capacity of approximately 1 million cu. ft./hr. The cleaned gas was distributed in mains which formerly carried town's gas; it was necessary, therefore, to ensure that no possibility of choking could arise. To this end oxide scrubbers were used, of which the main function was that of a filter rather than a desulphurizing unit. It was found in practice that, as well as providing a gas of which the dust content was less than 1 grain/100 cu. ft., the wet-cleaning system and oxide boxes reduced the sulphur content of the gas from a range of 85–105 to a range of 20–60 grains/100 cu. ft. Thirty per cent of the sulphur removal was accomplished in the washery, where soda ash was used in a closed circulating system with settling tanks, and 25% in the relatively small oxide boxes. After three years of working, the only corrosion trouble experienced in the whole unit, from producers to boosters, has been in the elbow at the point of entry of the downtake carrying the hot raw gas to the cooling tower. This freedom from corrosion is ascribed to the addition of soda ash to the circulating wash-water, the *p*H value being kept at about 7·5. The point at which corrosion took place was conducive to the formation of an almost stagnant film of water containing a relatively high concentration of sulphur dioxide absorbed from the gas.

A second plant was of similar type, but in this case the bulk of the sulphur was required to be removed. Accordingly, larger oxide boxes were installed. A system of rotation of the order in which the gas passed through the boxes was used in which partial revivification of the oxide could take place *in situ*. As a result a high standard was attained, both of desulphurization and of the duration of the period before it became necessary to change the oxide in the boxes.

A considerable amount of investigation has been undertaken in connection with these units with regard to the question of sulphur balance. Various methods of sulphur determination have been employed, ranging from the use of the gas referees' apparatus to absorption in solutions of cadmium chloride, silver nitrate, or bromine, followed by volumetric or gravimetric analysis, but finality has not yet been reached on this question. The bulk of the sulphur in the gas is undoubtedly in the form of hydrogen sulphide; varying amounts of sulphur dioxide have also been observed, from a trace to about 15 grains/100 cu. ft. of gas obtained from cokes containing 1–1·5% of sulphur. An appreciation of the conditions in the producer which determine the proportion of sulphur dioxide present in the gas is of importance when considered in the light of the extremely corrosive nature of this constituent in the presence of moisture; this consideration necessitates suitable steps being taken to protect the various units in the cleaning and distributing systems. In this field there is need for further investigation.

The results of a study of the effect on gas quality of variations in the proportion of steam in the blast supplied to the producers are of interest. A comparatively large number of determinations of the calorific value of the gas were made at different blast-saturation temperatures by means of a Boys calorimeter; an analysis of the values obtained is illustrated in Fig. 2. It is well known that

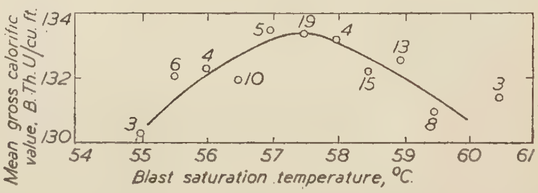


FIG. 2.—Variation in Calorific Value of Coke Producer Gas with Blast-Saturation Temperature. (The figures beside each point indicate the number of observations available for computation of the mean calorific values corresponding to the various temperatures.)

over the range of values normally employed the calorific value of producer gas tends to fall as the blast-saturation temperature is increased, but the occurrence of an optimum value (such as may be seen in Fig. 2) is not fully appreciated. It is thought that the cause of the decrease in calorific value as the saturation temperature is lowered below 57° C. may be due to the formation of clinker interfering with the uniform working of the producers.

With regard to the working temperatures attainable by the use of coke producer gas, these naturally depend on the degree of preheat employed in the case of both the gas and the air. Temperatures of well over 1200° C. could be readily obtained by using the raw gas at a temperature of approximately 250° C. with air preheated to 350° C. When cold, cleaned gas was used with air, again at a temperature of 350° C., in a furnace which had been originally designed to burn town's gas, a temperature of only 1125° C. was practicable with burners giving a good standard of flame admixture, but no special degree of intensity of air/gas mixing. No difficulty has been experienced in attaining temperatures of up to 1200° C. when using the cold gas in a furnace equipped with regenerators for preheating the air.

Although the highly toxic nature of carbon monoxide gas is well known to those familiar with blast-furnace practice, it may happen that gas plants of this type might be installed in works where the operatives are unaccustomed to it. In such cases, particularly where high pressures are

employed, special safety precautions and frequent testing for leakages are necessary. The palladium chloride technique [8] for the estimation of carbon monoxide concentration has been found to be useful in this respect.

Liquid Fuels.

Liquid fuels combine some of the advantages of gaseous fuels with a number of the disadvantages of coal and coke. Burner design has reached a stage whereby a sufficient degree of uniform atomization may be obtained to ensure complete combustion without the use of excess air. By suitable placing of the stock in the furnace to avoid premature chilling of the flame, and by good maintenance of the burners and atomizing equipment, no difficulty need be experienced owing to inefficient combustion. During the war years the shortage of petroleum fuel-oil has led to the development of a standard creosote-pitch mixture.[9]

Liquid fuels require the service of such ancillary plant as tanks, heaters, and pumps, and care is needed on the part of the furnace operator to ensure their efficient use. Minute attention to detail is required if the best results are to be obtained; for example, when shutting down burners it is necessary to protect them from radiation from the furnace chamber, as such radiation may cause the formation of a coke-like product able to choke the burner. Nevertheless, in situations where a suitable gas supply is not available, the need for the use of liquid fuel is likely to increase. If future developments in the treatment of coal, made with the object of obtaining an increase of the chemical products, should be successful, there will always be scope in the field being discussed for the use of by-product fuel-oil.

A further specialized application of liquid fuel is that of tar injection to low-grade gases (*e.g.*, in the open-hearth furnace) but controversy seems to range round the economic advantages of this measure. The problem is not likely to arise in works of the type the practice of which is discussed in this paper until an economical means has been developed of desulphurizing and detarring bituminous-coal producer gas.

III.—Developments in Furnace Design and Construction.

The principal developments under this heading fall into the following classes :

(i) General mechanization of furnace operation.

(ii) Improvements in instruments and automatic control.

(iii) The use of waste heat; recuperation; reduction of storage losses by the use of hot face insulation, and by the use of porous brick linings.

(iv) The use of forced circulation of the furnace gases.

(i) *Mechanization.*

General mechanization has extended to the use of moving hearths, either in annular rotary furnaces or in continuous-bogie-type furnaces. The main advantage of the former type has been the value of a hot hearth in ensuring quick heating and temperature uniformity in reheating. Where the material is of too massive a type to permit of the direct transfer of the cold charge to the hot rotary hearth, a continuous solid-hearth preheating furnace has been used. The use of the continuous-bogie furnace has enabled relatively heavy charges to be carried through continuous furnaces, both for reheating and heat-treatment. Conveyor furnaces of a multitude of types continue to be developed—pushers, rollers, walking beam (for sheet annealing), and rotating cylinders (for small parts). Economy arises through the saving of labour, the increase of output, and a much higher standard of uniformity of heating.

For reheating billets for piercing operations, gas-fired rotary-hearth furnaces utilizing both town's gas and coke producer gas and fitted with metallic recuperators, air/gas ratio control, and radiation-pyrometer control at the start and finish of the soaking zone, have eliminated a considerable degree of machining of the resultant forging; at the same time, the higher standard of temperature uniformity attained has resulted in an improvement in the accuracy of piercing.

Walking-beam furnaces have permitted considerable advancement in the standard of treatment of sheets, and the use of compartment furnaces with push-through bogies and forced gas circulation has resulted in a considerable increase in output from heat-treatment furnaces.

The " top-hat " furnace, with tubular elements carrying the heating gases, has been applied to sheet and wire treatment in which controlled atmospheres are used. This type of furnace is, in a sense, mechanical in that a chamber cover may be moved from one batch of charge to another, after a treatment involving a required cycle of temperature change has been carried out.

There has been a considerable development of mechanical furnace-auxiliary devices of all kinds. Some typical examples are :

(*a*) In gas burners; air/gas ratio control, combined with draught control, operated from a master controller governed by the furnace temperature. This would appear to be the ideal combination of mechanical controls to ensure perfect combustion and an ideal rate of heat

input, the two major requirements in control requisite for economical working.

(*b*) In charging and discharging machines; an advanced standard of mechanization has been reached in the former in regard to ease of control and size, and in the latter with respect to rapidity of quenching and removal from the quenching bath after the required period of immersion.

(*c*) In dampers and hearths; jointed heat-resisting metal bricks or plates to overcome distortion and cracking.

The problems of mechanization are bound up with two major lines of scientific progress: (i) Those fundamental advances in engineering science which are applicable to furnace practice, and (ii) the properties of the materials used in the construction of mechanisms, more particularly those involving the effect of high temperatures. The former depends upon external agencies and general progress in mechanical engineering science; it contains no specific problems which are not also of much wider interest. The latter involves certain critical properties peculiar to the conditions of furnace practice, such as resistance to creep, the effect of expansion in repeated heating and cooling, and resistance to the chemical effect of furnace atmospheres, in all of which research is continually being pursued by the interested organizations.

(ii) *Improvements in Instruments and Automatic Control.*

The contributions of physical science to engineering practice during the past decade have been outstanding. In the development of instruments for the more efficient use of fuel, electrical mechanisms, enriched by the use of the amplifying valve and the photo-electric cell, play a part of rapidly growing importance. In the next few years it is probable that electronic devices of many types will become available for use in instruments which are likely to be suitable for furnace practice. The ideal to be aimed at is the automatic furnace, but there are many limitations to be placed upon the attainment of this goal; some of these limitations are purely sociological in character. Thus it has often been urged that the search after merely push-button control may eliminate from a process that exercise of human intelligence and keen-eyed curiosity on the part of the operative which is desirable in any industrial operation. High-temperature processes require in their application methods which are simple and absolutely reliable (at present possibly over-sanguine demands), but it remains in such cases a desirable aim that automatic mechanisms should be reduced to the simplest terms. Naturally the number of instruments required and their function must be related to the size and economic importance of the heating unit. The efficient performance of an open-hearth furnace, the reheating plant feeding a large continuous mill, or a large battery of boilers may well merit a well-equipped instrument panel which cannot be justified in the case of smaller units.

In general, one master controller should be sought and this should be regarded as an integral part of the furnace unit. The experience drawn upon in this paper in regard to the use of instruments would suggest that there should be:

(*a*) An autographic record of the critical control feature. (Perhaps the best example of this is in an allied industry—a cement kiln, in which the oxygen content of the exhaust gases from the kiln is recorded.) In the heavy industries generally the critical feature may be temperature, or rate of fuel input. In open-hearth furnaces new and important developments are the roof pyrometer and the immersion thermocouple.

(*b*) Means to observe or control the air/gas ratio or flow.

(*c*) Means to maintain balanced draught. A sensitive draught-gauge before the outlet damper is always worth while.

Simple, robust, and readily accessible instruments are as important as the furnace itself and no furnace which does not operate purely on a push button should be without its proper complement of these accessories.

Further, a branch of the subject which could profitably merit attention is the development of a relatively simple mechanism—sufficiently robust for workshop conditions—for automatically controlling draught. There is probably no greater source of heat losses in industry than the improper draughting of furnace plant. Surveys of the composition of the furnace atmosphere at different levels and locations will often reveal unexpected results which the unaided skill of the operator may well fail to detect.

As a pointer to the significance of air inleakage, a difference of from 200° to 400° C. has been observed to have occurred in the temperature just above a bogie hearth following a tightening-up of the efficiency of the sand seals and the elimination of door leakage.

(iii) *Waste-Heat Utilization.*

The utilization of waste heat is frequently in the main an economic rather than a technical problem. This applies particularly in the case of the waste-heat boiler in which problems of design and efficiency have received considerable attention in the past, and the elements determining the output of steam from the plant can be readily ascertained. In general, technical opinion favours the use of the fire-tube boiler for a number of

reasons, which include the facts that the fire tube is easier to clean, and that the handling of large volumes of exhaust furnace gas at relatively low temperatures involves heavy draughting conditions apt to give rise to air inleakage if suitable provision for its prevention is not incorporated in the boiler design. If this latter limitation is taken care of and provided that proper provision for the cleaning of the tubes is made, there seems to be no reason why a water-tube boiler should not also be satisfactory. There are distinct advantages in the use of the higher steam pressures to be obtained, provided of course that a use for the steam can be found and that the temperature and weight of the gases permit an economical rate of evaporation to be attained. The problem is one on which further enquiry may not be unprofitable for those who are looking for new developments in this branch of waste-heat recovery. Alternatively, can it be said that a state of apparent finality has been reached in the design of the waste-heat boiler?

TABLE III.—*Air Preheating: Characteristics of Fuels.*

Fuel and Heating Value.	Air Required for Combustion of 1 lb. of Fuel.		Volume Required for Release of 1,000 B.Th.U.		B.Th.U./cu. ft. of Products.	Sensible Heat, % of Gross Heat.		Potential Heat Available for Heat Recovery in Cooling of Gases from 1200° to 600° C., %.	Relative Index of Air Preheat Obtainable, col. 4 × col. 8 / col. 3.
	Lb.	Cu. ft. (at 60° F.).	Air, cu. ft.	Waste gases, cu. ft.		1200° C.	600° C.		
	1.	2.	3.	4.	5.	6.	7.	8.	9.
Coal 14,500 B.Th.U./lb.	10·1	132	11·0	11·7	86	48·3	21·7	26·6	27
Coal 12,750 B.Th.U./lb.	7·1	116	11·0	11·9	84	49·3	21·5	27·8	30
Fuel-Oil . . .	14·0	184	9·85	10·4	96	46·8	21·5	25·3	27
Coke-Oven Gas (475 B.Th.U./cu. ft. .	Air-vol./gas-vol. 4·06		8·55	10·0	100	48·1	20·9	27·2	32
Producer Gas (163 B.Th.U./cu. ft.) .	1·28		7·85	12·7	79	65·6	29·8	35·8	58
Blast-Furnace Gas (92 B.Th.U./cu. ft.) .	0·69		7·50	16·7	60	79·1	34·2	44·9	100

Recuperation.

The advent of heat-resisting metals into engineering practice has resulted in the establishment of the metal recuperator. The greater compactness of the unit, its accessibility, ease of repair, and the absence of leakage in a proper design, make it much superior in furnace practice to the older type built of refractory material. The metal recuperator may be placed on the crown of the furnace as well as in the flues, and higher velocities of the heat-exchanging gases may be carried, with a resultant increase of the overall heat-transfer coefficient and better utilization of available heating surface. Further, recuperator tubes may be incorporated in flues in the furnace walls so that the heat storage in the furnace structure may also be picked up in the preheated air and/or gas. A frequent problem in a recuperator is how to raise the value of the heat-transmission coefficient on the waste-gas side of the heat-exchanging wall. In a nest of metallic tubes this coefficient is normally low, because of the usually low velocities of the gases passing to the exhaust unless an induced draught fan is employed. The importance of gas radiation in heating has only been appreciated in relatively recent years. Gas radiation may be picked up by additional refractory walls, which in turn reradiate to the heat-exchanging surface of the recuperator. The proportion of heat radiated from the refractory surfaces from this source may amount to an additional 30% at 800° C., as compared with the small proportion transferred by convection.

The relative merits of preheating the air used in conjunction with different fuels is apparent from the data given in Table III. The percentage of the potential heat of the fuel which is available for heat recovery as the products of combustion are cooled from 1200° to 600° C. is shown in column 8 of that table. In columns 3 and 4 are given the volumes of air and waste gases respectively which are involved in perfect combustion in order to release 1000 B.Th.U. An approximate relative index of the air preheat obtainable for a given drop of temperature in the waste gases is provided in column 9, the index being obtained from the expression (column 4 × column 8)/(column 3). The results indicate the degree to which the lean gases are particularly good subjects for recuperator practice, and that, with good heat-recovery, they can be made thermally efficient in use.

A metallic recuperator applicable for waste-gas temperatures of up to 1000° C. or more and used in combination with an exhaust fan, is probably the most effective appliance of heat recovery in pre-

heating practice. When operated in conjunction with a chimney, difficulties may arise; a chimney is not a satisfactory controllable draught-engine (though its cost in capital outlay and of operation may appear attractive) and it does not reach its full efficiency until the maximum temperatures in the furnace are approached, whereupon the draught is generally required to be reduced.

walls, and show the relationship between the wall thickness and the time required to reach within a specified temperature interval short of the maximum attainable at full heat saturation of the wall. From these data it is apparent that the so-called "steady conditions" are rarely reached in practice and that any calculations of heat storage based on such conditions are only roughly approximate.

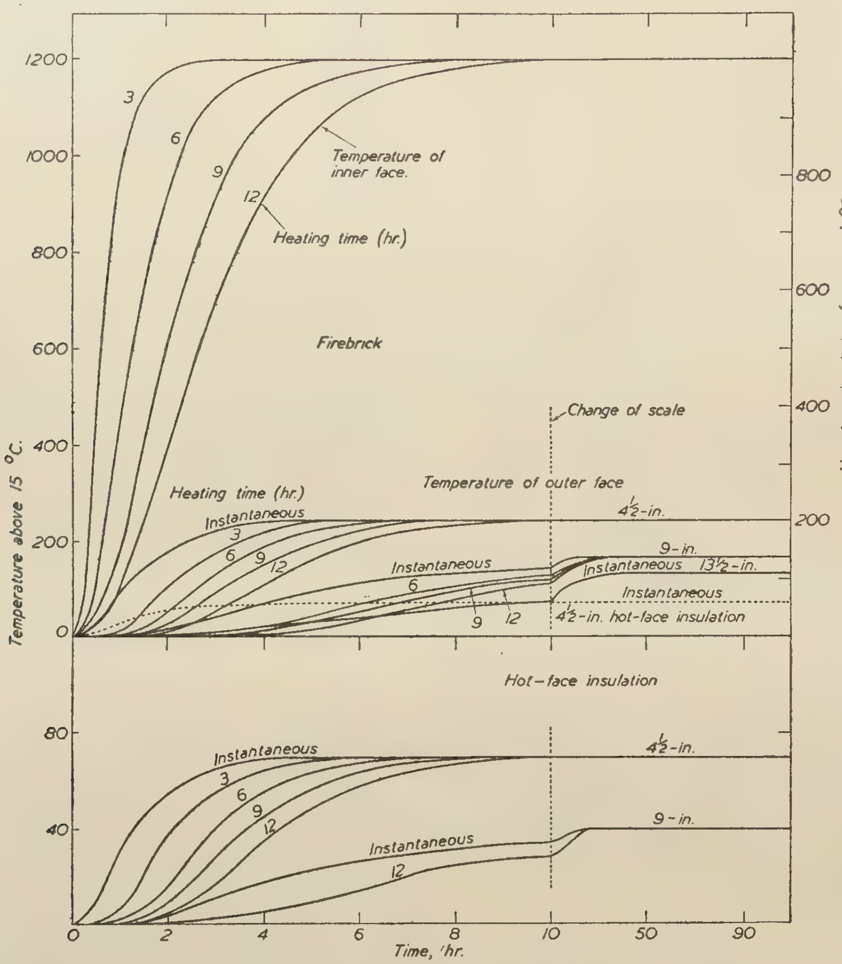


FIG. 3.—Temperature/Time Curves for External Surface of Various Types of Furnace Wall, Corresponding to Typical Heating Curves for the Inner Face.

Reduction of Storage Losses.

Progress has been made in the study of the heat storage in furnace structures and of the means to be taken for its reduction. Methods have been described,[10] utilizing machine forms of calculation, for the determination of the heat storage, under conditions of variable flow of heat, for the typical conditions of intermittency experienced in normal practice. By these means the economical thicknesses of brickwork and of insulation can be established for conditions other than those encountered under steady conditions. The data in Table IV., apply to perfectly insulated firebrick

Unlagged walls of 9-in. firebrick and 4½-in. hot-face insulation, when subjected to cyclic variations of temperature (6 hr. heating, 6 hr. soaking, and 6 hr. cooling) showed that cycles of outer-face temperature could be repeated after a second cycle of temperature changes had been passed through, that is, after the lapse of 36 hr.

Temperature/time curves relating to the external surfaces of firebrick walls and insulating refractories have been derived for different rates of heating of a type normally encountered in practice. Fig. 3, taken from the paper already referred to[10] (*loc. cit.*, p. 197), illustrates an example

of the technique. The data provide a general guide for establishing economy in intermittent practice of any particular type of wall. A point of fundamental importance is that developments of the machine methods of computation now in hand enable difficulties frequently associated with the existence of a thermal-diffusivity variable with temperature to be overcome, as well as permitting a detailed study of the behaviour of compound walls.

Table IV.—*Time (Hr.) Required to Reach Within a Specified Temperature Interval of the Maximum for Full Heat Saturation.*

Normal firebrick walls perfectly insulated.

Temperature Interval at Firebrick/Insulation Interface, ° C.	Wall Thickness, in.		
	4½.	9.	13½.
10	17	68	153
20	14	56	126
50	11½	46	103

Considerable investigation has been made into the properties of the refractories required to provide what has been termed " hot-face " insulation, that is to say, insulating firebricks of low heat capacity and possessing suitable chemical and physical properties to meet the requirements associated with the conditions within the working chamber of the furnace.

The mechanical properties essential are mainly a question of the behaviour of the brick in handling and transport. A cold crushing strength of 150 lb./sq. in. has been suggested as a tentative minimum.[10] The thermal advantage of the brick in reducing heat storage is approximately inversely proportional to its bulk density. In a furnace wall in practice, the temperature gradient across the wall is steep because of the highly insulating character of the brick, and the mean temperature is thereby reduced. Accordingly, for this reason, the brickwork as constructed could be expected to be capable of exerting a greater stability in service than might be expected from test data. The expectation of durability from this cause has been confirmed in panel tests. The usual problems of resistance to spalling, to slag and oxide fume, and to abrasion, arise in this class of refractory to a greater degree than with dense refractories, so that there is a limit to the locations at which they may be used. Thus they are not usually suitable for hearths, door jambs, burner blocks, or bridge walls.

The Importance of Gas Permeability.

The importance of the gas permeability of the refractory structures used has been frequently overlooked in furnace construction. All furnace walls not specially protected are permeable to gas. If the difference in pressure between the furnace chamber and the external atmosphere is appreciable there is a tendency either for hot gas to flow outwards or for an inleakage of cold air from the atmosphere; both effects may result in a lowered thermal efficiency. A good diatomaceous insulating brick may have a permeability of well under 1 British unit (cu. ft./hr./sq. ft./ft. at 1 in. W.G.), but some of the porous insulating firebricks examined have been found to have surprisingly high permeabilities. In practice the permeability becomes reduced, owing to the effect of temperature on the viscosity of the gas. Ignoring the effect of temperature and possible changes in the brick on heating it is found that, for a case in which the porous brick has a permeability of 12·8 British units and a mean thermal conductivity of 1·68 B.Th.U./sq. ft./hr./° F./in., over the range of temperature involved, the heat loss for a 9-in. wall with a temperature gradient of 1000–80° C., and a pressure difference of 0·2 in. W.G. across the wall, is respectively 309 B.Th.U./sq. ft./hr. for non-permeable conditions and 427 B.Th.U. for outward permeable flow. The difference in the heat loss amounts to an increase, due to permeable flow, of 38%. These facts point to the need for close joints and external plating and indicate the existence of a problem not yet solved by the makers of the porous bricks.

Fortunately these limitations are not universal, as entire walls and crowns of heat-treatment furnaces have been constructed with this type of refractory and are giving satisfactory operation. Normally, the hearth (for obvious reasons of durability) must be constructed of hard, dense refractories, but the question of insulation arises, as the zone of variable heat-soakage may extend to a depth of about 20 in.

Permeable Furnace Walls.

An interesting new construction in which the products of combustion are exhausted through the walls of the furnace, these walls being made of a permeable material, has been described by Anderson, Gunn, and Roberts.[11] The advantage of this construction over the orthodox design is that it results in the sensible heat of the waste products of combustion being used to supply the heat storage of the furnace wall. At the same time a more rapid attainment and a more even distribution of furnace temperature are practicable. The design has been incorporated in a variety of furnaces, including bogie-hearth furnaces with hearth dimensions of up to 13 ft. 8 in. × 10 ft., wire patenting furnaces, natural-draught oven-furnaces for carburizing, and a relatively high-temperature furnace for special heat-treatment. Automatic controls which give command of burner

input and furnace pressure have been incorporated. The authors of the paper referred to, in describing this development, have proposed a formula to define the saving over a non-permeable furnace in the case of town's-gas firing as follows:

$$P = \left(1 - \frac{C - 0{\cdot}11t_0}{C - 0{\cdot}11t_2}\right) \times 100\%$$

where

P = percentage saving,
t_0 = temperature (° F.) of the furnace gases just before entering the wall,
t_2 = annulus temperature (° F.), the annulus being the chamber outside the permeable wall into which the waste gases are exhausted.
C = gross calorific value of the gas, B.Th.U./cu. ft.

The proposal raises some controversial questions, as the apparent saving would depend in this contention upon the capacity of the refractory material of the furnace to absorb heat and so lower the value of the temperature t_2. Questions which appear to require to be answered in this respect are: "To what degree must the total heat-capacity of the wall be increased to accommodate the porous lining?" "Can an increase in such heat capacity be fairly credited to the performance of the furnace?" and "How would a heat balance of such a furnace compare with that of a furnace of identical size of working chamber and doing the same work, in which the walls and crown were constructed of hot-face insulation?" Also, "How would two furnaces, each equipped with an efficient heat-recovery unit (recuperators, regenerators, or any other mechanism for heat recovery) compare, one with the permeable lining and one without?" Further applications of this design and reports of furnace performance in which fuel consumption and load are related for a range of different loads, should be looked for with interest.

(iv) *The Use of Forced Circulation of Furnace Gases.*

It is well known that radiation either from solids or gases is the major factor in heat transmission at high temperatures, and that for low temperatures convection becomes the more appreciable factor.[12] In the absence of adequate experimental work on convection in furnace chambers recourse must be had to the work done on heat transmission in boilers and heat exchangers, where the value of high flow velocities in convection has been demonstrated, particularly in the case of fire-tube boilers. In recent years the principle of convection heating has been applied to low-temperature furnaces. The fuel is burned in a separate chamber and the products of combustion are circulated to the furnace heating chamber through a suitable arrangement of ducts; they are then returned for mixing with fresh products of combustion and recirculated. Fans of the centrifugal impeller type are used, constructed of heat-resisting metals capable of withstanding the range of temperatures in which convection heating is advantageous, that is, up to about 750° C. Both forced and induced circulation of the hot gases have been applied, with or without reversal of the direction of flow through the heating chamber, the gases being in circulation at such a velocity that the volume of gas circulated may be as much as 60 times the volume of the products of combustion. Forced circulation is also applied in other designs by means of propeller-type fans incorporated in the furnace chamber. This latter practice originated with electric furnaces, but in general it is less effective in attaining rapid and uniform heating than that in which the centrifugal impeller is used in a closed circuit. Thermal efficiencies of the order of 33% have been obtained in such furnaces under conditions in which soaking periods required for completing metallurgical changes have been twice as long as the period required for heating up to temperature. An extremely high standard of temperature uniformity is attainable, *e.g.*, a difference of only 2° C. over a length of 25 ft., in a vertical cylindrical furnace. High rates of output are attainable where the shape and section of the charge are such that the ratio of surface area to mass is favourable, and the circulating gases are able to penetrate the charge.

A limited portion only of the fundamental data extant can be applied to this problem, as there is a scarcity of heat-transfer data applicable to furnace chambers of industrial size or to large flues. Calculations of convection in the fire tubes of steam boilers give surface conductances of the order of 10 B.Th.U./sq. ft./hr./° F., whereas values obtained in practice are materially higher, with which fact is associated the influence of gas radiation.[13] On *a priori* grounds the surface conductance due to gas radiation would be expected to increase with the length of the radiant beam, whereas the effect of convection becomes reduced with an increase in the mean hydraulic depth of the gaseous stream. On the other hand dilution of the gaseous stream by the inleakage of cold air would result in a reduction of gas radiation from two causes, *viz.*, the fall in temperature and the lowering of the concentration of the radiating constituents (carbon dioxide and water vapour). Heat transmission is increased with increase of velocity, but at the same time the power consumed in the circulating gases is a factor of economic importance. Although the fan power varies directly as the flow, surface conductance by convection varies with the velocity to a power which lies between 0·8 and 0·56, according to the conditions. Large-scale survey investigations are required to fill the gaps in the existing knowledge.

IV.—Organization and Methods for Obtaining Fuel Efficiency.

The question of organization for fuel efficiency in any industry may be approached in two ways. One is from the standpoint of the individual works, and the other embraces the wider considerations of the industry as a whole, together with such items of national policy as are pertinent to the issue. Both of these approaches may be affected by the corporate action of external organizations.

The previous section of this paper, in which were described some of the more recent major developments in furnace design, gave an indication of present-day trends in furnace practice. In all the cases discussed the implications with regard to fuel economy are obvious. Considerable economies can be achieved in existing plant, however, by the adoption of a firm policy directed towards that end. Indeed, despite the savings in fuel which have been effected during the war years, it is the authors' opinion that the still wider application in industry generally of the fundamental principles of combustion could result in further economies, comparable with those already realized. It is intended in this section firstly to discuss certain aspects of this question as relating to the individual works, after which some of the broader issues will be considered, and the need for progress along certain lines suggested.

Fuel Saving in the Individual Works.

The first essential in any systematic attempt at fuel economy is the keeping of proper records relating to fuel consumption and output. So much has been said and written on this subject that further elaboration of it is unnecessary. It is essential, however, that such records should be put to effective use and, in this connection, the need for regular plant-survey work may be mentioned. Valuable as records of plant performance are, they are capable only of exposing departures from normal practice: they do not usually indicate the cause of any such discrepancy nor do they show whether or not, or in what manner, the usual standard of performance may be improved. These facts can only be determined by the carrying out of a proper survey of the plant in question. In some cases a few simple tests, such as the analysis of samples of the furnace atmosphere, or a pressure survey of the system, may suffice, while in others a more detailed investigation involving observations over a protracted period, possibly with the help of recording instruments, may be required. The important thing is to know where the heat units are going and to this end the drawing up of a heat balance or a Sankey diagram is often helpful in presenting a clear picture of what is happening. Such a balance may be simple, giving major

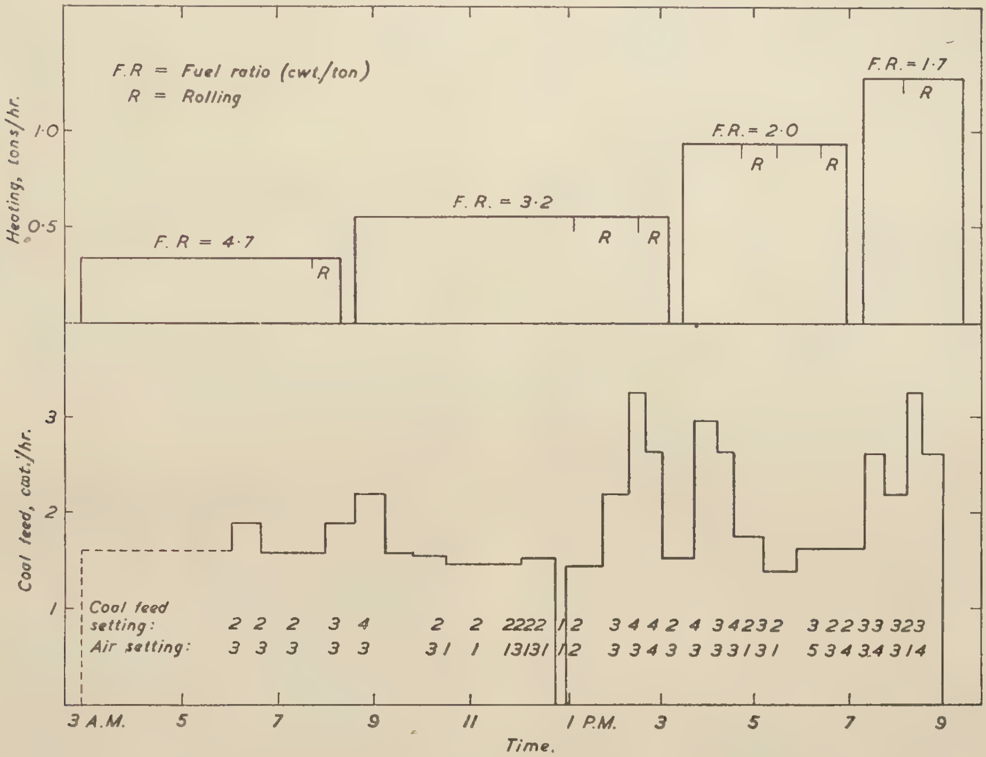


Fig. 4.—Variations in Rates of Heating and Fuel Input for Stoker-Fired Rolling-Mill Reheating Furnace.

items only, or complex, splitting each item down into smaller units, as the case warrants.

The following typical examples illustrate the manner in which plant survey work, which is virtually a practical means of applying existing knowledge, may be used to improve performance. It will be seen that such surveys are capable of indicating the need on the one hand for modifications in the light of more recent knowledge and, on the other hand, for special maintenance work, the need for which may otherwise remain undiscovered.

(i) *A Regenerative Ingot-Reheating Furnace.*

The furnace concerned was of the batch type; heat balances drawn up for a number of heats revealed the following :

	Percentage of Heat Input.
Useful heat in charge.	7·9–20·9 (depending on the tonnage heated).
Heat in waste gases.	Approx. 20
Radiation and convection losses from external surfaces.	12·9–20·4
Heat storage in furnace structure, and unaccounted-for losses.	43·9–53·5

In this case it is apparent that the major loss of heat is in the furnace structure, and the appropriate lines of improvement suggested accordingly included a modification of the brickwork, with a view to the reduction of its thermal capacity.

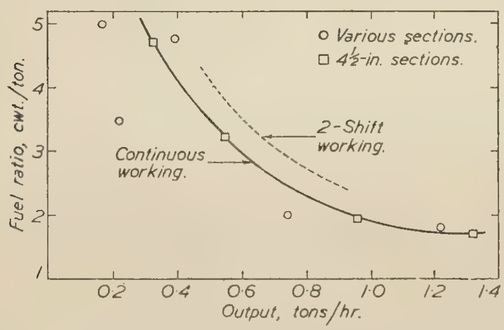


FIG. 5.—Relationship between Fuel Ratio and Rate of Output for Stoker-Fired Rolling-Mill Reheating Furnace.

(ii) *Comparison of Batch-Type Stoker-Fired and Hand-Fired Rolling-Mill Reheating Furnaces.*

This particular investigation was instigated for the purpose of determining the cause of the low life of the hearth refractories in the stoker-fired furnace. The rate of fuel consumption, rate of output, waste-gas composition and temperature, and the draughting conditions were logged throughout a number of working periods; examples of the results obtained are shown in Figs. 4 and 5. Fig. 4 gives the time variations of the rate of coal feed and the rate of heating in the case of the stoker-fired furnace and illustrates the wide variations in the heating rates required (which were partly due to shop requirements). Fig. 5 is a plot of fuel ratio against rate of output, again for the stoker-fired furnace, in which the relative performances for continuous and two-shift working are compared.

The reason for the low life of the hearth refractories was found to be insufficiently fine control of the rate of coal feed and air flow. When these were corrected the advantages of stoker firing over hand firing were such as to make possible the attainment of a fuel economy of up to 30%. The results of the investigation also indicated that a saving of from 10–30% of the fuel consumption was possible by the adoption of continuous working in preference to two-shift working.

(iii) *A Forced-Circulation Coke-Producer-Gas-Fired Heat-Treatment Furnace.*

In this case, trouble was being experienced owing to slow heating, which necessitated smaller loads, with consequent further lowering of furnace efficiency. The results of surveys of the fuel consumption, and of the temperature, pressure, and analyses of the circulating gases at different points in the system led to the following conclusions :

(*a*) Fluctuating gas pressures pointed to the occurrence of water in the gas supply mains.

(*b*) The combustion conditions, though not ideal, were not the major cause of the inadequate performance.

(*c*) The chief cause of the slow rates of heating being experienced was leakage of the circulating gases at the reversal valve, resulting in the heating chamber being partially short-circuited.

(*d*) A contributory factor was excessive heat loss from a non-operative door seal and cracks in the furnace superstructure.

Attention to these points, together with the correct setting of the air and gas valves, resulted in a reduction of the fuel consumption per unit of output by approximately two-thirds. This saving could be attributed mainly to the fact that the improved furnace performance enabled larger loads to be carried. A comparison of the performance of the furnace before and after the adjustments were made is given in Fig. 6.

This was a somewhat abnormal experience, but it points to what may occur even in well-managed plants and with the latest types of equipment available, unless attention is applied in the manner described. Many more examples could be quoted, but these few should suffice to show the importance of plant survey work.

Loading of Furnaces—The Importance of Planning.

This problem has been repeatedly stressed in the literature of the subject. The suggestion is ventured that the main source of improperly loaded furnaces arises in the planning of the installation. The accurate forecast of shop requirements is essential. Furnaces cannot be worked efficiently if they are to deal only with occasional large masses, or to operate at the maximum practicable rate of output, or to carry loads of too variable a character. Every duty

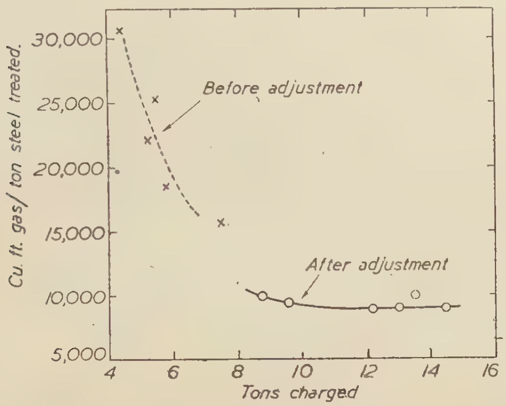


FIG. 6.—Relationship between Fuel Ratio and Weight of Charge for Forced-Circulation Heat-Treatment Furnace.

which a furnace may be called upon to fulfil is associated with specific dimensions of hearth and heating surface, as well as thickness of refractory walls and insulation, together with other factors which are capable of enabling the maximum efficiency to be attained. While much more work in certain fields is required before it can be said that the effects of all the factors involved have been completely elucidated, sufficient knowledge of the subject already exists to warrant the expenditure of considerable thought and effort in arriving at the optimum design to suit the conditions envisaged. If, owing to some unanticipated change in shop demands, the furnace duty should change, it might actually pay, under certain circumstances, to sacrifice the existing unit and rebuild in accordance with the new requirements.

A further aspect of the subject of planning requires an examination of the whole sequence of operations undertaken. It may be possible to utilize the heat rejected from a high-temperature process in one working at a lower level, although opportunities for taking advantage of this device occur more infrequently in the iron and steel industry than in other spheres. Space-heating requirements for buildings, however, may be capable of being met by previously untapped sources of waste heat; in this connection an example quoted by Faber in a recent paper,[14] although outside the industry, is of interest. In the paper is described the manner in which low-grade heat, possibly even at atmospheric temperature, may be economically upgraded to temperatures suitable for space heating by the panel system by means of the heat pump. Several examples of large plants utilizing this system, mainly on the Continent and in the U.S.A., are described, amongst which is mentioned the system installed at the Bank of England, where the source of low-grade heat is the cooling water from the Diesel engines in the power station. When one considers that in the iron and steel industry the equivalent of probably millions of tons of coal is lost annually in the form of low-grade waste-heat, one does well to consider the possibilities of such schemes.

Education and Research.

For the carrying out of work of this and analogous kinds it is apparent that in the future considerably more attention must be given to the question of education than has been the practice in the past. In the fuel efficiency campaign organized by the Ministry of Fuel and Power during the war the value of education has been recognized and many requirements have been determined which should be included in the permanent structure of the educational ladder of the future. Happily, all the organizations interested are giving attention to this matter. The Institute of Fuel, in conjunction with the Ministry of Education, the Ministry of Fuel and Power, the City and Guilds of London Institute, and other important bodies are considering how provision may be made for the institution of systematic training in fuel technology for all ranks of personnel engaged or likely to be engaged on these problems in industry. The existence of an educational ladder with the possibility of qualifying at each stage constitutes an incentive to the aspirant after useful knowledge in this subject. The shortage of fuel and its economic position is likely to provide another incentive for those elements in industry which are responsible for policy.

Not only is there the problem of the man who is able to take advantage of the normal educational resources of the country, but there remains the important question of the training of the operative. In this respect new methods have to be applied. These involve primarily the matter of practical instruction, the organization of demonstration plants, and the provision of instructors. Further, there is much scope for the type of handbook specially designed for the use of the practical man. Last but not least, there is the question of what is to be done about the man who has the obstacle of communications to contend with owing to the distant location of many important works from suitable centres where instruction may be available.

The general question of fuel research is at the moment one of some complication, and the need for co-ordination of the many-sided approaches to the problem is apparent. Co-operative work has been the keynote of scientific advance during the war; it would be a pity if the fruitful lessons of such a development were lost.

Problems Still Awaiting Solution.

In the course of the foregoing discussion many problems have already been indicated. The following is a list of further suggested lines of research, in the form of more or less major questions of general interest:

(1) Is powdered coal to be a fuel of the future, or will the development of the mechanical stoker entirely supplant this medium?

If the use of powdered coal in metallurgical practice is to be further developed the following factors will require attention:

(i) The laws of flow of mixtures of pulverized coal and air, in particular with regard to the influence of the fineness of division and the character of the coal.

(ii) Influence of flow velocity on the deposition of dust, and its bearing on the technique applied.

(2) Designs of gas burners in use are legion. Can some common specifications be devised which characterize the essential features of burner design for specific uses?

(3) An investigation is required of the causes of stratification and irregularities of flow of hot gases in furnace chambers and large ducts, and the derivation of the laws of flow and pressure drop in such conditions; the subject has particular reference to forced circulation.

(4) What is the specification of a satisfactory valve or damper and how is that specification influenced by the temperature range involved? A specific case is that of the valve required for controlling the flow of tarry gas.

(5) In furnace hearths, what is the ideal thickness for specific uses, and what is the ideal method of construction? How should bogie hearths be sealed to prevent air inleakage? Can better means than at present exist be found for turning over ingots, blooms, and billets in the soaking zone of reheating furnaces?

(6) A systematic study of the outstanding problems relating to the use of steam in iron and steel works practice is needed.

(7) The use of the heat pump already referred to in the present paper has possibilities in connection with the recovery of waste heat.

(8) Other requirements are:

(i) Simple coal meters applicable to band and bucket conveyors and to chutes.

(ii) A heat flux-meter not involving the use of water.

(iii) A sensitive air-meter applicable to natural-draught furnaces, for use at the air intake.

(iv) A means to measure the stresses encountered in furnace crowns.

The Determination of Physical Constants.

Much attention has been given in the past to the subject of heat transmission. For this work to be capable of exerting its full use it is necessary for much further investigation to be done on the determination of the physical constants involved. The laws of fluid flow at high temperatures, and the transmission of heat to and from moving gases in small ducts are fairly well understood.[15] In relation to this particular matter, the thermal conductivity and the viscosity of the normal furnace gases are known for the separate constituents of industrial gases. No relation has yet been traced, however, between the values of these individual constants and the corresponding coefficients for the industrial gases encountered in practice, except in the case of viscosity at low temperatures.[16] Thus McAdams states[15] (*loc. cit.*, p. 415) when giving the Prandtl numbers $C_p\mu/k$ for gases and vapours at 1 atm. pressure and 212° F.: "The effects of temperature and pressure are uncertain, and for the present it is recommended that $C_p\mu/k$ for gases be taken as independent of temperature and pressure, except near the critical region." The values for C_p, μ, and k are available in the literature [16] for certain specific cases, and for certain ranges of temperature. An extension of this data appears to be called for, as well as a method for calculating the properties of mixtures of the permanent gases at high temperatures.

In dealing with the highest temperatures in industrial practice (*e.g.*, steelmaking) the lack of high-temperature thermal data is very much apparent. The technique involved in the determination of such data is obviously difficult and tedious, and accordingly unattractive to the individual scientific worker. The determination of such constants as the latent heat of steel and of the heats of reaction of slag-forming materials leaves much to be desired, but such constants require to be definitely determined if the accurate thermal performances of high-temperature furnaces are to be measured; numerous other advantages are also to be gained, from the standpoint of the scientific technique of the processes involved.

The questions raised in this paper are not in any sense exhaustive. The wide range of the subject would preclude any such possibility within the compass of a single communication. It is hoped, however, that the points raised will at least arouse controversy, and thereby bring into prominence those problems which would appear at the present time to be most worthy of attention.

Acknowledgment.

The authors are indebted to the Directors of Messrs. Hadfields, Ltd., for permission to publish this paper.

REFERENCES.

1. A. Preece, G. T. Richardson, and J. W. Cobb: *The Iron and Steel Institute*, 1936, *Special Report No.* 14, p. 215.
2. A. Preece and others: *The Iron and Steel Institute*, 1939, *Special Report No.* 24, p. 9.
3. A. Preece and R. V. Riley: *Journal of The Iron and Steel Institute*, 1944, No. I., p. 253 P.
4. R. Jackson and others: *Journal of The Iron and Steel Institute*, 1944, No. II., p. 211 P.
5. J. E. Garside, J. S. Forsyth, and D. T. A. Townend: *Journal of the Institute of Fuel*, 1945, vol. 18, p. 175.
6. D. T. A. Townend and others: *Institution of Gas Engineers; Fellowship Reports*, 1939–40, 1942–43, and *Interim Report*, 1941–42.
7. W. A. Bone and G. W. Himus: "Coal, Its Constitution and Uses." London, 1936: Longmans, Green & Co.
8. Department of Scientific and Industrial Research: "Methods for the Detection of Toxic Gases in Industry". Leaflet No. 7: Carbon Monoxide. London, 1939: H.M. Stationery Office.
9. Ministry of Fuel and Power, Committee on the Efficient Use of Fuel: *Fuel Efficiency Bulletin No.* 36, 1945.
10. R. J. Sarjant: *Institute of Fuel War Time Bulletin*, 1945, (June), p. 189.
11. R. H. Anderson, D. C. Gunn, and A. L. Roberts: *Institute of Fuel War Time Bulletin*, 1945, (Oct.), p. 19.
12. "Efficient Use of Fuel," Chapter 13. London, 1944: H.M. Stationery Office.
13. R. J. Sarjant: *Journal of the Society of Glass Technology*, 1929, vol. 8, p. 175.
14. O. Faber: "The Value of Heat with Special Reference to the Heat Pump," *Institution of Mechanical Engineers Preprint*, 1945, (Apr.).
15. W. H. McAdams: "Heat Transmission." New York and London, 1942: McGraw-Hill Book Co.
16. H. M. Spiers: "Technical Data on Fuel" (fourth edition), p. 56 London, 1937: British National Committee, World Power Conference.

[This paper was discussed jointly with the preceding one by M. Tigerschiöld on "Fuel Problems in the Swedish Iron and Steel Industry" and the following one by N. H. Turner and F. A. Gray on "Fuel Utilization in Iron and Steel Works."]

FUEL UTILIZATION IN IRON AND STEEL WORKS.*

CONSIDERATIONS OF SOME PROBLEMS.

By N. H. TURNER (Appleby-Frodingham Steel Co., Ltd., Scunthorpe) and F. A. GRAY (Research and Development Department, The United Steel Companies, Ltd., Stocksbridge, near Sheffield).

Synopsis.

Problems met with in current fuel-utilization practice at integrated and non-integrated iron and steel works are briefly discussed. These problems are chiefly concerned with blast-furnace-gas production, cleaning, and distribution; some remarks as to the effect on fuel utilization of possible future modifications in blast-furnace practice have been added. The application of by-product gases to steelworks uses and the general question of heat conservation are also considered.

A comparison is made of the operating results at the melting shops and mills of the Appleby and the Templeborough Works. The paper concludes with some indication of what has been achieved in respect of fuel economy at certain subsidiary plants of The United Steel Companies, Ltd.

I.—Introduction.

Fuel is to-day the major item in the cost of production of finished steel, especially when, in the term "fuel consumed," that needed for the generation of the power purchased from outside sources is included.

It has been said that the successive processes at present used in the manufacture of iron and steel are thermally inefficient and that it is time that new methods were introduced. Although some justification exists for such a statement, and while it may be that the years to come will bring the desired improvements, it is in the meantime imperative to aim at making existing plants as efficient as possible, and in this way reduce the fuel consumption to a minimum.

To this end it is necessary:

(*a*) To utilize fully the by-product gases.

(*b*) To prevent the loss of latent or sensible heat existing in the material produced, after completion of the melting or heating process.

(*c*) To cause the necessary heat transfer from the fuel into the material being processed to take place with as high a degree of thermal efficiency as possible, and to use power in the most economical manner.

Integrated iron and steel plants represent one step towards the fulfilment of the first two conditions, but much has still to be done before the large amount of high-grade heat going to waste to-day is recovered, for instance, that lost with the blast-furnace slags, open-hearth slags, coke at the ovens, or from ingots as cast, and steel as rolled.

The points mentioned under (*c*) are receiving constant attention. The question of a decrease in the amount of low-grade heat going to waste with the flue gases, with the cooling water, and by radiation from the furnace shell must remain in the forefront. Some improvements have already been achieved by (i) use of better refractories, coupled with more efficient thermal insulation, (ii) extensive application of artificial draught (permitting more up-to-date means of waste-heat recuperation), (iii) fuller utilization of furnace capacity, &c. Further improvements may also be expected from partial replacement of the combustion air by oxygen, made possible by the reduced cost of production of the latter.

On the power side, the total elimination of avoidable losses would be accelerated by a more intensive application of technical methods in the study of the general operation of the plant.

A more extensive treatment of the various subjects raised would have been undertaken if more time had been available for the preparation of this paper. The treatment of each heading is thus brief, and is confined to some general considerations.

The paper concludes with some indication of what has been achieved in respect of fuel economy at subsidiary plants of The United Steel Companies, Ltd. (the integrated iron and steel works of the Appleby-Frodingham Steel Co., Ltd., and the steelworks of Steel, Peech and Tozer and of Samuel Fox and Co., Ltd.).

Some comments are also made in the paper on certain problems which have been dealt with, and a comparison is made (Figs. 1, 2, and 3) of some of

* Received February 5, 1946.

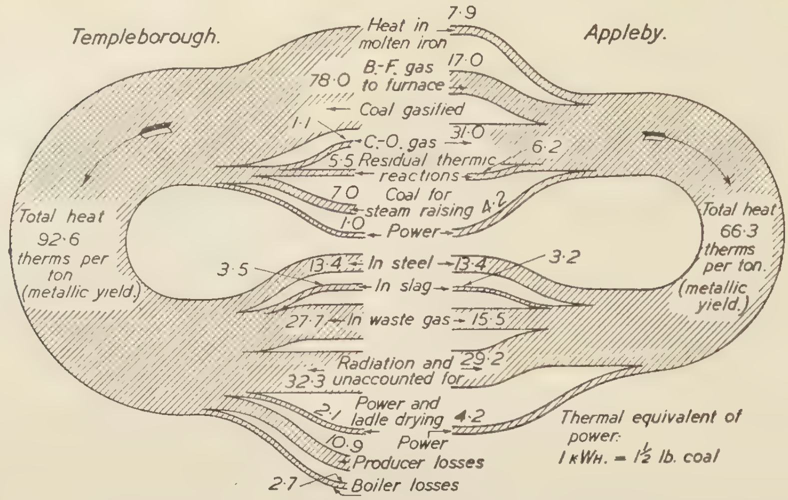


FIG. 1.—Heat Balance: Melting Shops. (In this and subsequent heat balances, heat consumptions are for a typical week and include fuel used at week-ends.)

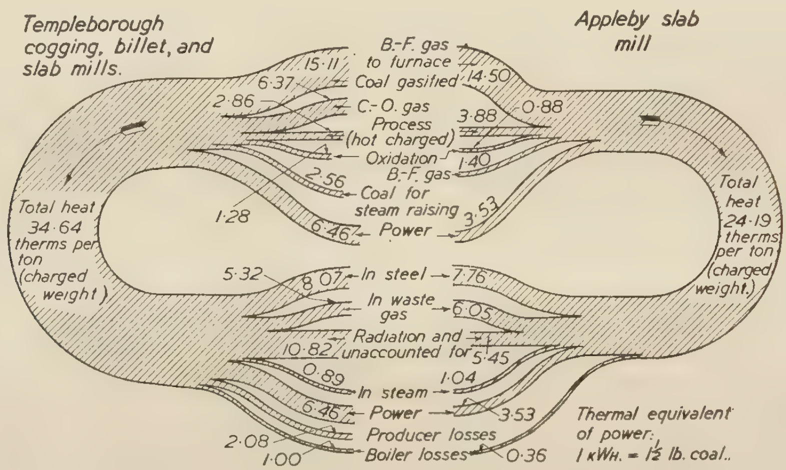


FIG. 2.—Heat Balance: Cogging, Billet, and Slab Mills.

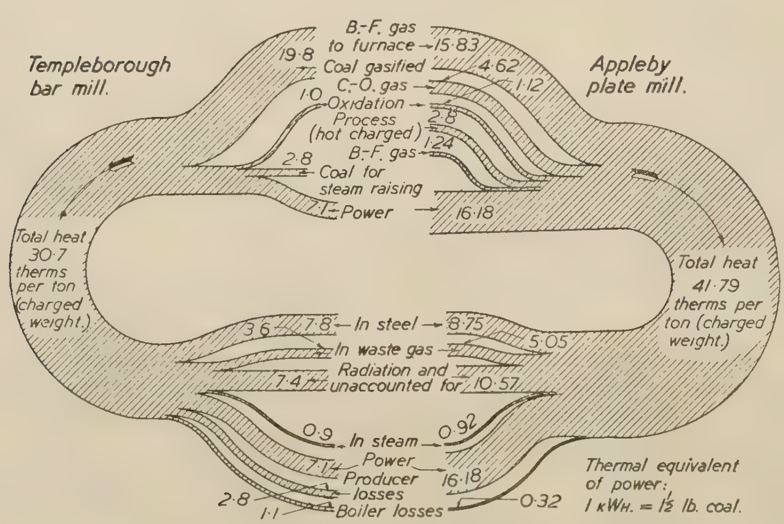


FIG. 3.—Heat Balance: Bar and Plate Mills.

the operating results at the melting shops and mills of the Appleby and the Templeborough Works.

II.—General Considerations.

Utilization of Blast-Furnace Gas.

In the case of blast-furnaces working mainly with British ores, coke consumption per ton of iron may vary from about 18 to 30 cwt. in exceptional cases, depending on the characteristics of the furnaces and their burdens. The blast-furnace gas produced (after allowing for incidental losses) varies with coke consumption from 116,000 to 193,000 cu. ft. per ton of iron and has a calorific value (similarly varying) from 95 to 117 B.Th.U./cu.ft.*; this represents 47 to 58%, respectively, of the net calorific value of the coke used. An appreciable proportion of this by-product gas is used in raising the air blast to the required pressure and temperature (thereby returning some heat to the furnace) and in supplying heat to ancillary units. These items, grouped under the heading of blast-furnace service but excluding electric power, absorb a proportion of the gas produced, this proportion varying from 35 to 43%, according to the efficiency and extent of the ancillary plant employed. There remains about 60%, of the blast-furnace gas to be otherwise utilized, representing 60 to 120 therms/ton or, at the ruling price of coal, 10*s.* to 20*s.* per ton of iron. The utilization of this gas is therefore a matter of consequence. The generation of electric power is an obvious method and one which is commonly practised. The power requirements of a blast-furnace plant vary greatly according to the nature of the raw materials to be handled, but where a low-quality ore is crushed, graded, bedded, and otherwise dealt with according to the latest practice, the total electric power required can be generated with a heat consumption of 21 therms/ton of iron. This will absorb no more than one-third of the blast-furnace gas surplus and although it might be suggested that additional electric power could be generated and sold, this is not always a practical or an economical proposition.

It is here that the integrated iron and steel plant comes in, not necessarily as a so-called "balanced plant" (a somewhat meaningless expression possibly coined at one time to hide an excessive consumption of coke at the blast-furnaces), but as a plant making use of all the blast-furnace gas and producing finished steel with a minimum overall fuel consumption.

Reverting to the blast-furnace plant having the equivalent of from 60 to 120 therms/ton of iron to dispose of, how can this potential heat be utilized to the best advantage in a steelworks producing, say, mild-steel plates as the final product? The melting shop is equipped with open-hearth furnaces and active mixers, and shows a yield of 90%. The slab mill and the plate mill give an overall yield of 70%, it being assumed that the scrap from the mill is returned to the melting shop and that no intermediate product is sold. Under these circumstances the melting shop can produce ingots for a heat consumption of 64–66 therms/ton, and the mill will produce plates for a heat consumption of 26–27 therms/ton of ingot, charged weight.

It is important at this juncture to emphasize the advantage of operating the melting shop with hot metal, as the heat content of the metal reaching the melting furnace can be assessed at 8 therms/ton of metal, a portion of the original heat content having virtually been lost by the metal in its passage through the mixer. The value of the heat saved is still greater when it is considered that, owing to prevailing melting-furnace efficiencies, that heat could not be replaced for a lower expenditure of fuel than that equivalent to 35 therms/ton of metal.

It is to be noted that in the above instance the melting shop has been assumed to operate on producer gas and that the heat consumption has been given on the basis of coal used. The consumption of blast-furnace gas in the steelworks, therefore, would be confined mainly to the mill furnaces, where it amounts to the equivalent to 32–33 therms/ton of iron produced, still leaving a surplus of at least 27 therms/ton of iron (assuming a consumption of 18 cwt. of coke per ton of iron). This surplus is rather more than sufficient to generate the electric power for the blast-furnace plant; if the coke consumption at the blast-furnaces were slightly in excess of 21 cwt./ton of iron, the whole of the electric power for the blast-furnace and the steelworks requirements could be produced from surplus blast-furnace gas. If the blast-furnace operating conditions were such as to require a coke consumption much in excess of the latter figure, a considerable quantity of blast-furnace gas would be produced which could not be used, while the melting shop would still be operating on coal.

It is now common to find a coke-oven plant included in an integrated iron and steel works. As in the case of close association of the ironworks and the steelworks departments, the inclusion of a coke-oven plant shows advantages of no mean magnitude. The carbonizing temperatures generally employed are such that, with the regenerative facilities usually provided, they can be maintained by the combustion of gaseous fuels of low calorific values. It is apparent therefore that, by operating the coke ovens with surplus blast-furnace gas, a supply of high-calorific-value gas (coke-oven gas) is obtained which can

* Gas figures quoted are in terms of dry gas at N.T.P.

be used, for instance, in the melting shop. In effect, the coke-oven plant may be regarded as a "transformer," by virtue of the fact that the low calorific value of the input carbonizing gas is stepped up to the high calorific value of the output gas. Moreover, the total thermal value of the coke-oven gas produced is about 2½ times that of the carbonizing fuel used. It is therefore possible, in suitable circumstances, to use coke-oven gas (in conjunction with blast-furnace gas or by itself) in the melting-shop furnaces, thereby avoiding the conversion loss inherent in the use of gas producers. Although not readily assessable, the advantages of ease and closeness of control to be gained by using mixed blast-furnace and coke-oven gas, or coke-oven gas by itself, instead of producer gas should not be overlooked (although the melting-shop manager may have something to say as to some of the disadvantages). It is to be noted that the melting shop, working on these gases, can produce ingots at 55 therms/ton in contrast to a coal-equivalent of 64–66 therms/ton on producer gas.

Table I., based on various coke consumptions at the blast-furnace plant, shows how the fuel requirements of the various consumers can be met at a particular integrated works, assuming that the coke-oven plant produces all the blast-furnace coke required.

It will be seen that, in the case of the blast-furnace plant working on a coke consumption of 18 cwt./ton of iron, to operate the integrated plant in the most advantageous manner, the coke ovens should use coke-oven gas for carbonization. There remains sufficient blast-furnace gas and coke-oven gas for use in the melting-shop and mill furnaces. There is, however, an overall gas deficiency (excluding power requirements) of 4 therms/ton of iron which, for instance, might be balanced by producing 4% more iron and selling this surplus, or by the use of coal on the boilers. All the electric power required would have to be purchased. It may be noted in this instance that should the coke-oven plant be omitted, the melting shop would operate on coal, and the available blast-furnace gas would not be sufficient to generate all the electric power required. Therefore, merely from the point of view of surplus gas utilization, there is no direct advantage in this case in operating a coke-oven plant.

In the case of a coke consumption of 21 cwt./ton of iron, the same general arrangement of gas utilization would apply, but, in this instance, there would be a surplus of 17·5 therms available for the generation of electric power. If a coking plant is not included, the melting shop would again operate on coal, and the available blast-furnace gas would just balance that required for the generation of the electric power. Therefore, for the general conditions of plant operation so far assumed, this coke-consumption figure represents the borderline beyond which the operation of a coke-oven plant becomes a material factor in the utilization of surplus gas. Having otherwise determined that a blast-furnace plant shall operate with a coke consumption appreciably in excess of this limiting value for the complete utilization of surplus blast-furnace gas, the inclusion of a coke-oven plant presents considerable scope for variation in the application of other questions of policy. For instance, only a proportion of the coke requirements may be produced, or only a part of the melting shop may be operated with coke-oven or mixed gas and a larger proportion of power generated or *vice versa*. It may be expedient to sell a part of the iron production, or a part of the steel production in the semi-finished state.

TABLE I.—*Heat and Fuel Available and Required at an Integrated Iron and Steel Works.*

Production and consumption are per ton of iron produced.

Blast-Furnace Plant.			
Coke consumption, cwt./ton	18·0	21·0	24·0
Net coke weight, tons	0·90	1·05	1·20
Gross coke weight, tons	0·98	1·14	1·30
Net gas, therms produced	110	135	164
Blast-furnace service (excluding electric power), therms consumed	47·3	56·0	62·5
Surplus gas, therms	62·7	79·0	101·5
Electric power required, equivalent therms *	18	19	21
Coke-Oven Plant.			
Blast-furnace coke, tons	0·98	1·14	1·30
Coal as charged, tons	1·65	1·88	2·15
Gas, therms produced	88	100	115
Carbonizing gas, therms	36·3	41·3	47·0
Steam—process and boosting, &c. Gas, therms	14·2	16·1	19·0
Surplus gas, therms	37·5	42·6	49·0
Electric power required, equivalent therms *	3·5	4·0	4·5

Steelworks.		For Melting or Heating, therms.	For Electric Power, therms.
Melting Shop.			
1·23 tons ingots made, at 55 therms/ton.	B.-F. gas 24, C.-O. gas 44	68	5·4
Soaking Pits.			
1·23 tons ingots charged, at 12·0 therms/ton.	B.-F. gas	14·8	18·8
Reheating Furnaces.			
0·98 tons slabs charged, at 18·0 therms/ton.	B.-F. gas	17·6	
Boilers.	B.-F. gas	3·6	
		104·0	24·2

* 1 therm equivalent to 5·8 kWh.

Effect of Irregular Working of the Blast-Furnaces and of Future Developments in Blast-Furnace Practice.

The previous comments have been made on the basis of blast-furnace gas being available for utilization, but it is well known that there are at times deficiencies in the production of this gas, caused by, for example, a furnace coming off for relining, or one or more furnaces failing to produce their normal gas output during bad spells or in the course of maintenance repairs. Such facts have to be given full consideration when assessing the merits of power purchased *versus* power generated; in the case of power being generated, it has to be decided whether it should be obtained from gas- or steam-operated units, bearing in mind that the ease and quickness with which a boiler can be changed over from blast-furnace gas to stand-by fuel are considerations to weigh against a possible loss of thermal efficiency.

What the position will be with the advent of gas turbines is not fully clear, as development may take place along lines which may have the same advantages (from the point of view of stand-by fuels) as possessed by steam to-day.

It may be contended that a stand-by can be provided by having gas producers available when the melting shop is using mixed gas. The case is, however, very different; gas producers must either be started up well in advance of being required or be kept at the ready, which would no doubt involve, in either case, an appreciable overall loss of thermal efficiency. Furthermore, the disposal of the liberated coke-oven gas might not be entirely advantageous.

When the blast-furnaces are operating on lean ores with a low rate of coke consumption, the temporary deficiencies in blast-furnace-gas supply are likely to be accentuated by recurring periods of erratic working at the furnaces, when the need of gas storage and of units fitted for use of alternative fuel is all the more pressing.

With large blast-furnace-gas holders, the reserve of gas will allow sufficient latitude if a change over to alternative fuel should be necessary. In this way fuel waste can be eliminated, by avoiding the interference with proper combustion which may follow the simultaneous use of fuels with different characteristics in the same unit in order to be prepared for eventualities. The gas-holders would also even out the variation in quality of the blast-furnace gas inherent in erratic working, provided that the gas passes through the holders. Incidentally, this is a point of some importance when operating blast-furnace-gas engines.

When considering the complete utilization of the blast-furnace gas produced, consideration must also be given to the effect of future developments in the preparatory treatment of ores on the quality and quantity of gas produced and available.

Future developments may be expected on the lines of a more extended application of the ore-beneficiation processes described by Elliot,* and possibly in concentration of the ores by such methods as washing, magnetic separation, &c. Such developments in ore treatment may, in general, be expected to influence blast-furnace-gas quantity and quality in the following directions:

(1) By reducing the total heat requirements in the furnace, resulting in a reduced coke consumption at the tuyeres, with a corresponding reduction in blast volume and in top-gas volume per ton of iron. A reduction in calorific value is also probable, as it can be assumed that the total quantity of CO_2 from ore reduction will tend to remain constant so that, with less coke gasified, there will be a lower ratio of CO to CO_2 in the blast-furnace gas leaving the furnace.

(2) By reducing the carbon solution which occurs in the bosh or stack as the result of direct ore-reduction, or as the result of CO_2 from the carbonates reacting with the iron.

(The higher ratio of indirect to direct reduction which follows an increase in reducibility of the ore, together with the external removal of CO_2 by calcination, will—both factors tending to reduce the solution of carbon—result in a decrease of the amount of CO formed, this in turn causing a pronounced reduction in the calorific value of the blast-furnace gas, and a slight reduction of the gas volume.)

(3) By a direct reduction in the hydrogen content of the gas as the result of more complete external removal of water from the ore.*

In addition to these trends towards a reduced volume of gas produced per ton of iron and a lower calorific value of the gas, the fuel requirements of the external treatment of materials, if met by the use of blast-furnace gas, will still further reduce the quantity of gas available for steelworks or other purposes. Also, the reduction in calorific value may raise other problems, such as the increased difficulty (in certain cases of usage) of retaining the necessary temperature-levels without enrichment of the gas.

Future developments in blast-furnace practice may also take the form of oxygen enrichment of the blast, which, if adopted, will raise many problems in gas utilization and distribution. In particular, the reduced heat- and power-requirements of the blast, the change in composition

* *The Iron and Steel Institute*, **1944**, *Special Report No.* 30.

and increased calorific value of the top gas, and the consequent reduction in the amount of waste gases resulting from its combustion, will have to be considered.

Whatever line future developments may take, an adequate number of heat-consuming units will have to be equipped for the use of alternative fuel.

Effect of Cleanliness of Blast-Furnace Gas.

To make the most of the blast-furnace gas available, this gas must be cleaned. Different views, leading to much discussion, have been expressed as to the degree of gas cleanliness necessary for the various consuming units.

Apart from the difficulties of providing gases with various degrees of cleanliness (each with adequate storage), it would be necessary to balance the cost of the extra gas-cleanliness against the cost of extra cleaning or repair of the consuming equipment and the possible loss of efficiency of the units consuming the gas.

It has been claimed at times that stoves, furnaces, boilers, &c., have been able to operate on gas possessing a lower degree of cleanliness, but it is felt that no sweeping statement can be made on this subject without taking into consideration the method of gas cleaning. Between the dry and the wet methods with which the authors are fully acquainted, there are marked differences in the results, not so much in final dust content, which is somewhat similar in both methods, as in the nature and general physical condition of the dust remaining, and in the temperature of the gas.

The following remarks may illustrate this statement:

On leaving the dry gas-cleaning plant, the gas (with a dust content below 0·01 g./cu.m.) is well above its dew point, the temperature of the gas being some 60 to 70° C. above that of the atmosphere. Under these conditions there is no deposition of residual dust and the gas delivery header and mains in the immediate neighbourhood remain clean, but further along the main deposition of dust begins to take place, evidently at a very slow rate. This deposition starts at points where the average gas temperature is still above the dew point of the gas, and is probably caused by local cooling on the walls of the main, the hygroscopic nature of the dust possibly also having an influence on the adhesion of the deposits. The deposition continues until the gas is well below its dew point, when conditions seem to be reached in which the water condensed from the gas is sufficient to wash any further deposits into the drains; from this point the mains are clean. Furthermore, alkaline dust being the finest, a high proportion of this dust will remain in the gas after cleaning, to the detriment of any brickwork with which the hot products of combustion may come in contact. The location of the consuming unit in relation to the gas-cleaning plant has thus to be considered.

In the case of the wet process, the dust (free from the alkalies, which have been dissolved) remaining in the gas, having already been wetted as a result of the process, is almost wholly entrained by the water in suspension and of condensation and such dust will easily flow to the drains upon deposition, with the result that a main from a wet-cleaning plant always remains cleaner than that from a dry-cleaning plant.

Incidentally, a further point worthy of mention in connection with dry cleaning is the possibility of the dust removed from the gas-cleaning plant reaching a state where the amount of heat generated in it, in excess of that liberated by natural cooling, is high enough to set fire to combustible material such as bags, wooden wagons, &c., in which the dust may be contained or with which it comes in contact, this "spontaneous combustion" being caused by the presence of pyrophoric iron in the dry dust.

The use of dirty blast-furnace gas at a distance from the point of production has to a large extent ceased, but some ironworks units still have to make do with it and suffer all the concomitant evils: Incomplete combustion in stoves and boilers (sometimes even further accentuated by the presence in the dust of combustion inhibitors), poor efficiencies of the stoves as a result of dust deposition and glazing of the brickwork (causing a lessening of the conductivity of the surface layer of the checkers and necessitating more frequent stove changes), and excessive radiation losses owing to more stoves having to be put into commission. It is sincerely hoped that the increased value of fuel will lead works managements to give more sympathetic consideration to any suggestions from their respective fuel departments towards elimination of the use of gas in this condition.

Gas Control.

When the operation of the steelworks depends largely on the supply of blast-furnace and/or coke-oven gas, it is necessary to arrange a system of co-ordination of gas production and distribution; such a system is especially necessary for control (as far as control in such circumstances is possible) of the off-blast periods of the blast furnaces.

The co-ordination can best take the form of a properly manned and equipped gas-control station, but in its absence a makeshift organization will go a long way towards eliminating potential trouble.

The bases of any form of gas control are gas

measurement and the certainty that the amount of gas allocated to any particular consuming unit will remain at the set figure until a change is warranted. The benefits to be derived from the judicious use of industrial measuring instruments in the achievement of fuel economy have by now been fully recognized and, wherever the works management is progressive, full consideration is given for the provision of such instruments in the design of new plants.

With regard to existing plants, the instrumentation of some of them with even the minimum number of instruments may be difficult, owing to the layout of the works. In such cases the works fuel department has to manage with information which is far from being complete.

Generally, the extent of the instrumentation will depend on the amount of information required by the plant management, the fuel department, the cost department, and the plant operator.

The tendency towards a better-educated type of operator, able to reap the benefits of instrumentation, necessitates that adequate provision be made for the maintenance of the instruments, and it is nowadays quite common for iron and steel works to have a properly equipped instrument maintenance department.

More and more use is also being made of automatic regulators for the control of air and gas volume, pressure, and temperature. Control of this kind has developed to such an extent that it may soon be necessary for plant items to be designed for being automatically controlled, rather than simply having automatic controllers fitted to them.

A further development of automatic regulation will be for the remote control of certain co-ordinated units (*e.g.*, gas boosters in interconnected plants); such a trend is already evident and may in time make attendance unnecessary.

Application of By-Product Gases.

Integrated Works.

Apart from considerations of economics (which may have the larger bearing on the question), the choice of where best to utilize the by-product gases should resolve itself into the consideration of desiderata connected with the temperature to be attained and metallurgical factors (so far as furnaces are concerned); with boilers the necessity of making provision for the use of auxiliary fuels is the chief consideration.

It would thus seem that in the case of integrated iron and steel plants with coke ovens, the question as to whether the melting furnaces should be fired with coke-oven gas mixed with blast-furnace gas or with a tar fuel can be answered from the strictly fuel point of view by employing the method which will ensure the full utilization of the by-product gases available.

In the case of soaking pits and reheating furnaces, when enough blast-furnace gas is available the addition of coke-oven gas as a boosting agent should generally be limited (for metallurgical reasons) to use in the latter. Although the addition of coke-oven gas to blast-furnace gas may permit a simplification of soaking-pit design, to dispense with the preheating of the gas is not thermally economical.

As for the boilers, the question of solid *versus* liquid fuel as stand-by is again mainly one of economics, but when assessing the merits of pulverized fuel *versus* stokers one would tend to favour the former, as none of the special precautions required by stokers when gas is used as the normal fuel are necessary for the stand-by use of pulverized fuel.

When it has to be decided which units should first be taken off blast-furnace gas during periods of scarcity, it may be found that the least thermally efficient will show the greatest improvement when changed over to the alternative fuel; in this way the maximum amount of blast-furnace gas will be liberated for the use of the minimum amount of the other fuel. There may, however, be some other considerations to influence the order of priority.

Non-Integrated Works.

When coke-oven gas is available in non-integrated steelworks, it offers decided advantages as a source of high-grade heat. Care should be taken to ensure that this gas is applied, as far as possible, to processes where it can be utilized to the best thermal advantage. It should therefore be reserved for high-temperature processes. Where clean or raw producer gas is available, such fuel should accordingly be used for drying purposes and other low-temperature applications, where conditions permit. In special cases other advantages may outweigh these considerations.

The replacement value of coke-oven gas varies according to the purpose for which it is used; speaking generally, and from the standpoint of economics, it has its greatest value when used in small heating furnaces and its lowest value when used for drying purposes or as a supplementary fuel for steam-raising. Coke-oven gas should not be used for the latter purpose unless the gas would otherwise be lost at the coke-oven-plant bleeder.

Increases in thermal efficiency of from 15 to 50%, together with increased output, are possible by the replacement of producer gas and direct coal firing by coke-oven-gas firing in reheating furnaces. Of course, the increased efficiency attainable varies according to the efficiency of the furnace before conversion; thus, small direct coal-fired furnaces which have a low thermal efficiency show the greatest improvement when fired by

coke-oven gas. The coke-oven gas has therefore a high replacement value on such furnaces. On the other hand, where coke-oven gas replaces producer gas on an efficient continuous mill-furnace, the increase in thermal efficiency is comparatively small and may correspond only to the saving of the gas-producer heat losses. The order in which coal- and producer-gas-fired furnaces should be converted to coke-oven-gas firing, commencing with those on which the greatest savings can be made, is as follows:

(1) "In and out" direct coal-fired furnaces.
(2) Coal-fired continuous furnaces.
(3) Producer-gas-fired "in and out" furnaces.
(4) Producer-gas-fired continuous furnaces.

The heat-consumption/output chart (Fig. 4) for an "in and out" mill furnace when coal-

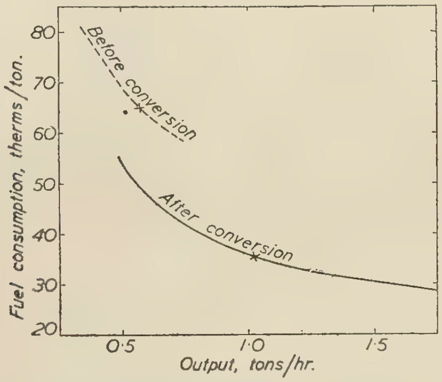


Fig. 4.—Heat-Consumption/Output Curves for "In and Out" Type Mill Furnace, before and after conversion to coke-oven-gas firing. (Crosses indicate average operation.)

fired and after conversion to coke-oven-gas firing, illustrates the reduction in heat consumption and the increase in output possible in such furnaces. In this particular case the converted furnace is now doing the work of two coal-fired furnaces.

While it may be claimed that the application of coke-oven gas (in amounts of up to 10% of the total heat input in the open-hearth furnace) as a supplementary fuel to producer gas may give some help during melting, it has been the authors' experience that the replacement value of coke-oven gas used in this way is low, being that of an equal number of thermal units of producer gas.

When there is sufficient coke-oven gas available (after satisfying the demands of the reheating furnaces) to permit 100% coke-oven-gas firing of the open-hearth furnaces, then the position is altered and the coke-oven gas has a greater value because of the elimination of producer costs. It is rarely possible to do this on account of the large quantities of coke-oven gas involved (such quantities may amount to, say, 90,000 cu. ft./hr. for one 80-ton furnace).

As in the case of the distribution of blast-furnace gas, adequate gas-holder capacity is necessary, not only to balance the rates of supply and demand but to provide storage for the gas produced during week-ends, when the steel plant is not working. Similarly, adequate instrumentation, pressure regulation, and a central gas-control station are necessary for the efficient distribution of coke-oven gas supplies.

The supply of coke-oven gas is generally regular in quantity and quality, in contrast to the variable nature of the blast-furnace gas supply; under normal conditions it is not necessary, with a properly designed and organized plant, to make provision for an alternative to coke-oven-gas firing of steelworks plant. During the war and at the present time, however, owing to the reduced amount of coke-oven gas available, it has been necessary to make good such deficiencies by the use of other fuels.

Heat Conservation.

The open-hearth furnaces in a steelworks are the major fuel consumers and for this reason alone demand special attention. It is desirable that a technical staff be allocated to, and entirely engaged upon, fuel utilization and control in the melting shop.

Good instrumentation is essential for the guidance of the furnace operator and to provide data for the efficient technical control of the furnaces.

Open-hearth furnace design has not fundamentally changed since the introduction of the process, and there is considerable scope for basic research on the subject.

The major heat losses (from the furnace structure and the waste gases) amount to some 60 to 70% of the heat input, as shown in the Sankey diagram (Fig. 1). An important factor affecting open-hearth efficiency is the small temperature-difference permissible, in view of the danger of melting the refractories. The provision of satisfactory bricks which will stand up to higher temperatures would improve the heat transmission to the charge and give increased rates of production; the use of such bricks would also permit the insulation of the furnace walls and roof and, in this way, reduce the structure losses to a material extent.

The principle of heat regeneration, making use of a portion of the heat content of the waste gases, which made the open-hearth furnace practicable has paved the way for general development of the technique of heat recuperation. The equipment used for the purpose may form an integral part of the unit or it may act as an ancillary, depending upon whether a certain amount of preheating of the gas and air used is essential or whether economic considerations dictate the

preferential employment of the waste heat in another direction.

When preheating the incoming air (or gas and air) the flame temperature may set a limit to the amount of direct recuperation desired but, in the case of a low-calorific-value gas (such as blast-furnace gas), a high degree of preheating is generally necessary; for maximum recovery it is imperative that the gas and air both be preheated, because of the ratio of waste gases to incoming air and gas and of the closeness of their specific heats.

The defects inherent in brick regenerators and recuperators have led to increased use of the metal-type recuperator, especially for temperatures below 800° C.; by taking advantage of the relatively high heat conductivity and low heat capacity of metal in contrast to brick, a good performance can be achieved in a much smaller space. It is a feature of the metal-type recuperator that the gas velocity is relatively high; consequently there may be an appreciable pressure loss through the unit, both on the waste-gas side and on the gas or air side. Because of this (and also on account of the further reduction in waste-gas temperature) it is usually necessary, for the proper operation of the furnace, to use boosting and exhaust fans; these fans will consume in power the equivalent of only 5–10% of the heat recovered.

The application of waste-heat boilers to furnaces provides a suitable method for recovery of the heat in flue gases, which cannot otherwise be returned to the furnace. The best case for a waste-heat boiler can usually be made for a unit with a large heat throughput (provided, of course, that the temperature of the waste gases is sufficiently high). The open-hearth furnace is a typical example of such an application. In such cases waste-heat boilers may result in the recovery of from 30 to 50% of the heat contained in the flue gases. The amount of steam generated is from 3000 to 15,000 lb./hr., depending upon the size of the furnace. Boilers used for this work should be of the high-velocity fire-tube type.

As regards reheating furnaces, particular care is necessary to ensure that an economic case for waste-heat boilers can be made out. Used with some of the old type of coal-fired reheating furnaces of large production capacity, waste-heat boilers can (and do) save considerable amounts of fuel. The policy here, however, should be the replacement of such furnaces by more efficient types which make the use of waste-heat boilers as an item of fuel economy unnecessary; reheating furnaces (with the exception of direct coal-fired furnaces) working at temperatures up to 1350° C. can, and should, be designed with this end in view.

As far as heat conservation in general is concerned, there are stages in the steelmaking process where more care should be taken. For instance, it has been said that heat is required to cool ingots from the casting to the rolling temperature; this statement, by its apparent absurdity, forcibly draws attention to waste of heat at this intermediate stage. A plant obtaining its steel from Bessemer converters is evidently better placed (from the point of view of heat conservation) than one making steel in large open-hearth tilting furnaces, where the amount of metal obtained from each cast is such that, without efficient planning, much heat loss is likely to occur. Some relief may be obtained by the use of Gjers pits, but particular attention must be paid to the design of these in order to ensure that their heat capacity is at a minimum, so that no more heat is lost from the ingot than that which is necessary to permit the temperature to even itself across the ingot section during the passage through the soaking pits.

III.—Progress Achieved.

In 1930, fuel departments were started in all the main works of The United Steel Companies to give specialized attention to the important subject of fuel economy.

As the result of close co-operation with the works departments, definite progress has been made. An outline of what has been achieved during the last decade is given below.

Old Blast-Furnace Plants.

Twelve hot-blast stoves have been relined for use with clean blast-furnace gas, the new burners being equipped with automatic air/gas ratio control. The present thermal efficiency of the stoves is 90% (against 65% previously), with further economies resulting from the smaller number of stoves in use.

The increased consumption of clean blast-furnace gas has necessitated the enlargement of the dry gas-cleaning plants by two units, and the development of an improved technique of cleaning-plant operation which permits 25% more output of gas without lowering the standard of cleanliness.

As far as possible, advantage has been taken of the dismantling of old plants to improve the layout of gas mains and so decrease pressure losses.

New Blast-Furnace Plant.

The modern South Ironworks Plant of the Appleby-Frodingham Steel Company has received, in the design of units concerned with fuel utilization, the full benefit of accumulated experience; particular attention has been given to ensure that pumps, gas-cleaning fans, gas boosters, &c., have their best efficiencies at or close to their normal duties.

In this connection, experience with the wet gas-cleaning disintegrators fitted at this plant is of interest. When first erected they greatly exceeded the specified power consumption; subsequent alterations made by the makers with a view to reducing the power required had also the effect of greatly increasing the throughput of gas without decreasing the degree of cleanliness.

Melting Furnaces.

The development in connection with open-hearth melting furnaces has been the complete rebuilding of a number of furnaces at the Templeborough and the Stocksbridge Works to modern Maerz and Venturi designs. This work has been completed at Stocksbridge and is continuing at the Templeborough Works, where provision has also been made for the use of coke-oven gas for ancillary purposes and for supplementing producer gas in the furnaces.

At the Appleby Works the melting shop has been enlarged by the addition of three up-to-date tilting furnaces and one mixer. Since the coke-oven plant has been put in operation the main fuel used is mixed blast-furnace and coke-oven gas.

For some years past it has been the policy to strengthen the control of fuel utilization in the melting shops by the employment of technical staff.

Heating Furnaces.

As the result of closer supervision by the fuel departments, all heating furnaces are better insulated and maintained (from the fuel-utilization point of view); more attention is also paid to the utilization of furnace capacities.

The main feature at the Templeborough Works has been the replacement of solid fuel and producer gas by coke-oven gas on a large number of furnaces. Where producer-gas firing has been retained, metallic-type recuperators have been installed to give higher furnace efficiencies. Similarly, at the Stocksbridge Works the trend has been the replacement of direct coal-fired furnaces by producer-gas-fired furnaces fitted with metallic recuperators.

Owing to war conditions causing a shortage of coke-oven gas, it has been necessary at Steel, Peech and Tozer's Works to convert certain furnaces back to coal and producer-gas firing. When coal firing has been re-introduced, underfeed stokers have mainly been employed, thus obtaining a greater efficiency than by hand firing. Similar difficulties at the works of Samuel Fox and Company have been met by the use of clean coke producer gas and raw coal producer gas.

All the old regenerative soaking pits at the Templeborough Works have been replaced by modern recuperative pits, giving a reduced fuel consumption. Also, the 40-in. cogging mill at these works has been replaced by a new 43-in. mill; this latter change has resulted in a reduced power consumption.

Preheating the ingots in continuous bogie furnaces has been introduced at Frodingham and at Appleby. At Appleby a new soaker, with air regeneration and gas preheating in a metal recuperator, has been built, and continuous bogie furnaces (heated with enriched blast-furnace gas) are now used for heating slabs to rolling temperature.

At the works of Samuel Fox and Company a similar furnace, fired with producer gas, heats cold ingots to rolling temperature.

Substantial improvement in fuel economy has been achieved at the Frodingham 15-in. mill furnace by increasing the proportion of hot-charged billets.

The Frodingham cogging and finishing mills are in the process of being converted from steam to electric drive. New soakers, fully instrumented and controlled, will be provided.

Gas Distribution and Control.

Templeborough Works.

In 1933, a coke-oven gas supply was introduced with the completion of a pipe-line connecting the steelworks with The United Steel Companies' Orgreave coke-oven plant. This measure formed part of a forward policy which to-day is being carried a stage farther.

The gas-distribution system is illustrated diagrammatically in Fig. 5.

The gas from the coke-oven plant, delivered to the steelworks through a 16-in. main three miles in length, is compressed to a pressure of 13½ lb./sq.in. at the coke-oven plant and reaches the steelworks gas-control station at a pressure of 9 lb./sq.in.; it is there reduced to, and controlled at, 6 lb./sq.in. for distribution.

The coke-oven gas is used at a pressure of 6 lb./sq.in. in the non-recuperative furnaces, but the pressure is reduced to 6 in. W.G. for the cogging-mill soaking pits and the Templeborough melting shop, as shown in the diagram.

The use and distribution of the gas is supervised from the central control house, where an attendant is always on duty and in touch with the coke-oven plant personnel and the gas supervisors in the steelworks. The control house is fitted with distant indicators showing the gas flow at various points in the system. A system of priority is used to adjust the demand to the supply.

It will be noted that a 3,000,000-cu. ft. gas-holder, situated at the coke-oven plant, is used to store a proportion of the week-end gas make and to assist in balancing the supply and demand. The gas-holder is gradually emptied throughout

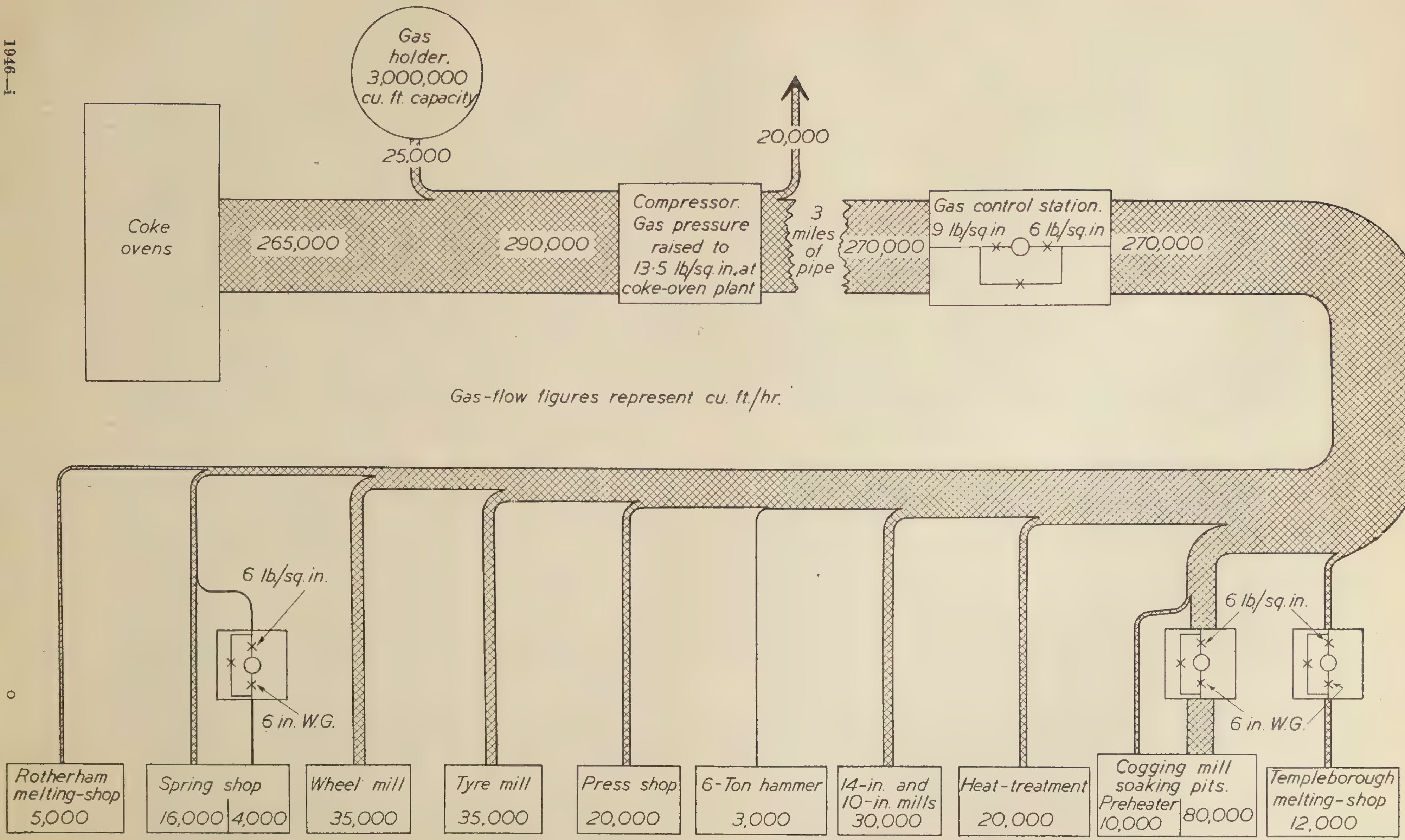


FIG. 5.—Coke-Oven-Gas Distribution for Templeborough Works.

the steelworks working week, according to an arranged schedule.

The gas supply from the Orgreave coke ovens is to be increased following the completion of additional ovens and the laying of a new 18-in. pipe-line over a distance of fourteen miles to supply coke-oven gas to the works of Samuel Fox and Company. Two additional gas-holders of 3,000,000 cu. ft. capacity are to be installed, one at the coke-oven plant and one at Stocksbridge. Additional coke-oven gas will also be made available for the works of Steel, Peech and Tozer by this extension.

Appleby-Frodingham Works.

The starting of the South Ironworks and Coke-Oven Plants, followed immediately by considerations connected with air-raid precautions, brought to a head the necessity for central gas control. The organization had to be treated as an emergency one and, so far, it has not been completed by the addition of a full complement of instruments.

The system of gas control, besides assuring a fair distribution of the blast-furnace and the coke-oven gases, has also been responsible for the more complete staggering of the off-wind periods at the blast-furnaces. The responsibility for the economic use of alternative fuels rests with the gas controllers. The gas-control post is continually manned.

Boilers.

Much attention is paid to water treatment to ensure a suitable water supply to the boilers. As a result the boilers have been maintained clean and free from corrosion.

Special care is taken to ensure that proper combustion is maintained and that the boilers are used at their optimum load. Whenever possible, alternative fuel is provided for the blast-furnace-gas fired boilers; coal, pulverized fuel, and pitch-creosote are the main stand-by fuels.

Among improvements in boiler plants are the following:

At Appleby-Frodingham: Two water-tube boilers, 350 lb./sq.in. pressure, total capacity 60,000 lb./hr., supplying steam in a closed circuit to a 6250-kW. turbo-alternator.

A battery of five Lancashire boilers changed to clean blast-furnace gas, with resultant increased output which normally does away with the necessity of using a second battery fired with dirty blast-furnace gas.

At the Stocksbridge Works: Following experimental trials, a specially designed boiler, with a capacity of 25,000 lb./hr., has been installed to burn a low-grade colliery-washery refuse containing 35 to 42% of ash with a small admixture of boiler slack (containing 15% of ash).

The refuse, a product of the washery at the Stocksbridge Colliery, was previously unusable in existing boilers and had to be dumped. This new boiler has been entirely successful and effects a saving of 5200 tons of good coal per annum.

Waste-Heat Boilers.

A number of such boilers are used in the Companies' open-hearth plants and at the blast-furnace gas engines, and further boilers are being installed.

Instruments and Regulating Equipment.

The extent to which instruments and automatic-control equipment is now being used is illustrated by the following examples of that provided on the latest open-hearth and continuous reheating furnaces.

Open-Hearth Furnaces.

Gas-pressure regulator(s).
Gas-pressure recorder(s).
Gas-flow recorder(s).
Air-flow recorder.
Furnace pressure recorder and controller.
Gas-checker draught recorder.
Air-checker draught recorder.
Stack-draught recorder.
Roof-temperature recorder.
Checker-temperature reversal indicators.
Checker-, flue-gas-, and gas-temperature recorder(s).

Continuous Two-Zone Slab-Reheaters.

Total blast-furnace gas-flow recorder.
Total coke-oven gas-flow recorder.
Mixed-gas flow recorder.
Blast-furnace gas pressure indicator.
Coke-oven gas pressure indicator.
Mixed-gas pressure indicator.
Gas-mixture regulator.
Gas-mixture pressure regulator.
Furnace-temperature recorder and regulator on each zone.
Six-point furnace temperature indicator.
Air/gas ratio regulator on each zone.
Furnace-pressure regulator on each zone.
Furnace-pressure recorder.
Reversal controller.

For the maintenance of such instruments a fully equipped instrument repair shop with a present staff of twenty has been in operation at the Appleby-Frodingham Works for the past fifteen years.

Thermal Insulation.

At all the works much attention has been paid for many years to the use of thermal insulation for the prevention of heat loss.

At Appleby-Frodingham this activity culminated in the formation of a Heat-Insulation Department, even before the Ministry of Fuel started its strong propaganda on the subject.

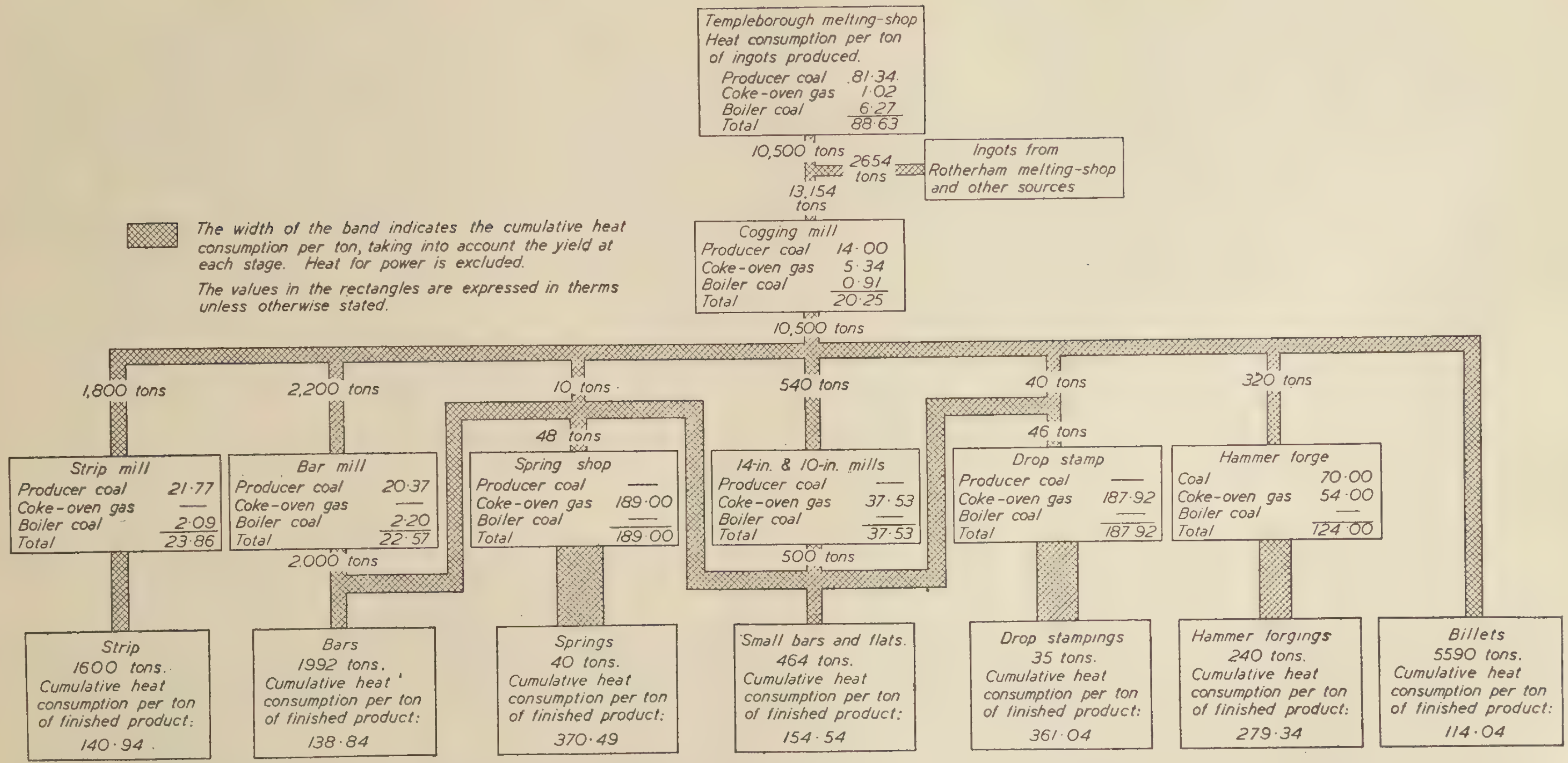


FIG. 6.—Furnace Heat-Consumption Chart for Templeborough Works. Except in the Templeborough melting shop, the heat consumption in each shop is given per ton of steel heated. The figures in tons give the relative quantities of steel at each stage (weekly basis). Boiler coal consumption is given for producers only.

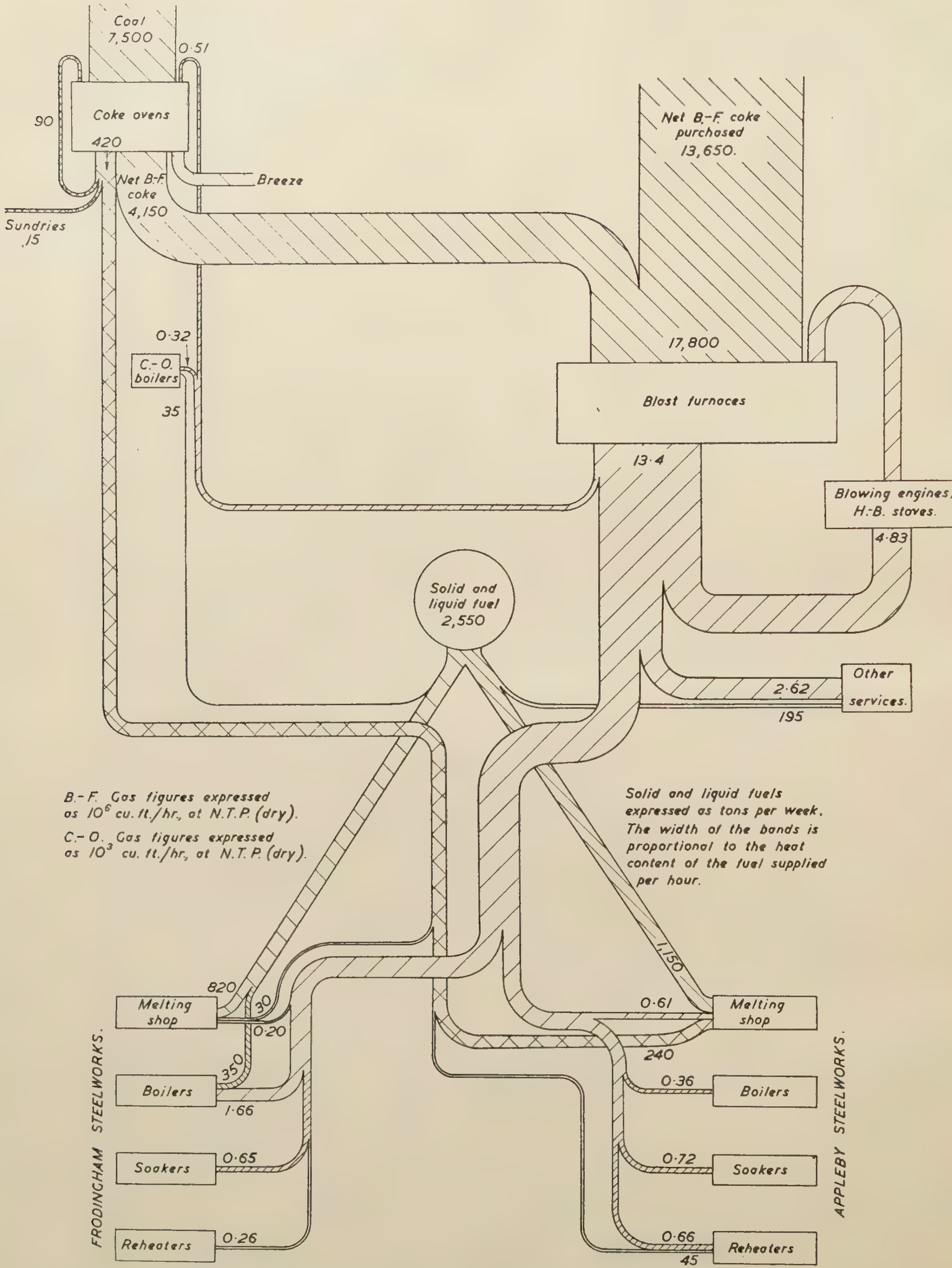


FIG. 7.—Present Fuel Distribution at Appleby-Frodingham Works.

Present Heat Consumption.

Diagrams (Figs. 6 and 7) show the present heat consumptions at the Templeborough Works and at Appleby-Frodingham. The diagrams illustrate how war-time and post-war conditions have affected the fuel economy of the plants.

It is interesting to note (Fig. 6) the relatively greater heat consumption for materials nearing a finished state as compared with semi-finished products (such as bars, strip, &c.). This emphasizes the necessity for close attention being paid to fuel utilization in the finishing departments as well as with the large production units.

ACKNOWLEDGMENTS.

The authors wish to thank the management of The United Steel Companies and Associated Companies for permission to present this paper.

Acknowledgment is also made to the staff of the Fuel Departments of the various works for their help.

APPENDIX.—*A Brief Description of Fuel-Using Plants.*

APPLEBY-FRODINGHAM WORKS.

Frodingham Ironworks.

Blast-Furnaces.	2 mechanically charged, 17 ft. hearth diameter. 2 hand charged.
Air Blowing.	1 steam blowing engine. 5 gas blowing engines.
Power.	4 gas engines.
Steam.	8 water-tube boilers—blast-furnace-gas fired, with coal as stand-by fuel.
Gas Cleaning.	1 dry plant: 3·5 × 10⁶ cu. ft. capacity. 1 wet plant: 1·1 × 10⁶ cu. ft. capacity.

North Ironworks.

Blast-Furnaces.	2 mechanically charged, 17 ft. hearth-diameter. 2 hand charged.
Air Blowing.	4 gas blowing engines. 2 turbo-blowers.
Power.	6 gas engines. 3 turbo-alternators.
Steam.	2 water-tube boilers—blast-furnace-gas fired, with pulverized fuel as stand-by. 2 water-tube boilers—blast-furnace-gas fired, with pitch-creosote as stand-by fuel. 13 Lancashire boilers—blast-furnace-gas fired, with coal as stand-by fuel. 1 waste-heat boiler on gas engine.
Ancillaries.	1 static ore-drier. 1 Greenawalt four-pan sinter plant. (Both fired with blast-furnace gas.)
Gas Cleaning.	1 dry plant: 5·8 × 10⁶ cu. ft. capacity.
Gas Holder.	1 dry: 2 × 10⁶ cu. ft. capacity.

South Ironworks (started 1939).

Blast-Furnaces.	2 mechanically charged, 22 ft. hearth-diameter.
Air-Blowing.	3 gas blowing engines.
Steam.	3 waste-heat boilers on gas blowing engines. 2 Economic boilers—blast-furnace-gas fired, with pitch-creosote as stand-by fuel.
Ancillaries.	2 rotary ore-driers. 1 two-strand Dwight-Lloyd sinter plant. (Both fired with blast-furnace gas.)
Gas Cleaning.	1 wet plant: About 11 × 10⁶ cu. ft. capacity. 1 small electrostatic-type plant, for supply of gas to gas blowing engines.
Gas-Holder.	1 wet: 3 × 10⁶ cu. ft. capacity.

Coke-Oven Plant.

Ovens.	Normal production: 5500 tons of blast-furnace coke per week. 0·54 × 10⁶ cu. ft. coke-oven gas per hour.
Gas-Holder.	1 wet: 3 × 10⁶ cu. ft. capacity.
Steam.	3 water-tube boilers—blast-furnace- or coke-oven-gas fired, with pitch-creosote as stand-by fuel.

Frodingham Steelworks.

Melting Shop.	4 tilting furnaces. Capacities: 120–175 tons each. Fired with producer gas enriched with coke-oven gas. 1 active mixer. Capacity: 400 tons. Fired with blast-furnace or coke-oven gas.
Mills.	1 36-in. two-high cogging mill. 1 32-in. two-high finishing mill. (Both steam driven.) 1 15-in. three-high electrically driven mill.
Soakers.	1 blast-furnace-gas fired bogie-type continuous preheater, with metallic air recuperator. 4 top-charged—blast-furnace-gas fired, with air and gas regenerators.
Reheaters	1 side-charged—blast-furnace-gas fired (for 32-in. mill). 1 continuous pusher-type—blast-furnace-gas fired (for 15-in. mill). (Both with air and gas regenerators.)
Steam.	14 Lancashire boilers—blast-furnace-gas fired, with coal as stand-by fuel. 2 water-tube boilers—blast-furnace-gas fired.
Power.	2 mixed-pressure turbo-alternators, operating from mill engines' exhaust.

Appleby Steelworks.

Melting Shop.	7 tilting furnaces of 250 and 300 tons capacity. 2 active mixers of 500 tons capacity. (All fired with mixed blast-furnace and coke-oven gas, with producer-gas as stand-by firing.)
Mills.	1 two-high slabbing mill. 1 two-stand two-high 7-ft. plate mill. 1 two-stand two-high 10-ft. plate mill. (All electrically driven.)
Soakers.	3 Gjers pits, each with six compartments. 1 bogie-type continuous preheater. (Blast-furnace-gas fired, with metal air recuperator.)

Soakers.	3 blast-furnace-gas fired, top-charged, with gas and air regenerators.
	1 blast-furnace-gas fired, top-charged, with air regenerators and metal gas recuperator.
Reheaters.	3 blast-furnace-gas fired (gas enriched if necessary with coke-oven gas). Side-charged, with gas and air regenerators.
	3 bogie-type continuous, with air regenerators, fired with mixed blast-furnace and coke-oven gas.
Ancillaries.	1 normalizing furnace, 7 ft. wide, blast-furnace-gas fired, with gas and air recuperators.
	1 annealing furnace, 12 ft. wide, blast-furnace-gas fired, with air regenerators and metal gas recuperator.
Steam.	2 water-tube boilers—blast-furnace-gas fired.

Templeborough Open-Hearth Melting Shop and Mills.

Melting Shop.	14 open-hearth furnaces, 80-ton fixed-type, operated on cold iron and scrap, and fired with producer gas from fourteen gas producers (10 ft. and 11 ft. in dia.); gas enriched if necessary with coke-oven gas introduced before the regenerators. Coke-oven gas also used for drying and preliminary heating of furnaces, drying of launders and ladles, and for heating of brick-tarring plant.
Steam.	3 Lancashire boilers (30 × 9 ft.) auto-stoker fired.
Cogging, Billet, and Slab Mills.	1 43-in. cogging mill (installed 1944), electrically driven by 15,500 h.p., D.C. motor, coupled to Ilgner set; designed for rolling up to 4½-ton ingots and 7-in. sq. blooms.
	1 four-stand 21-in. continuous billet-mill and
	1 six-stand 18-in. continuous billet-mill, driven by common 5000-h.p. synchronous motor.
	1 30-in. roughing mill, driven by 7000-h.p. motor.
	1 two-stand 21-in. slab mill, driven by 1250-h.p. motor.
Soakers.	32 cell soaking-pits (22 fired with producer gas, 10 fired with coke-oven gas). Each cell holds eight 3¾-ton ingots.
	2 small furnaces, fired by high-pressure coke-oven gas (for preheating high-carbon ingots).
	(Producer gas from three 11-ft. dia. gas producers. Coke-oven gas at 540 B.Th.U./cu.ft. from the works supply system).
Steam.	2 Lancashire boilers (30 × 9 ft.) auto-stoker fired.
Bar Mill.	1 six-stand 14-in. roughing mill and
	1 four-stand 12-in. finishing mill, driven by 3000-h.p. motor.
Reheater.	1 continuous furnace, 30 ft. wide × 40 ft. long. Capacity 40 tons/hr., producer-gas fired.
	(Producer gas from two 10-ft. dia. gas producers.)
Strip Mill.	1 six-stand 12-in. roughing mill.
	1 six-stand 12-in. finishing mill.
	(Driven respectively by 1500 and 2500-h.p., A.C. motors.)
Reheater.	1 continuous furnace, 30 ft. × 20 ft. Capacity: 20 tons/hr., producer-gas fired. Producer gas from one 11-ft. dia. gas producer.

[This paper was discussed jointly with the preceding two by M. Tigerschiöld on "Fuel Problems in the Swedish Iron and Steel Industry" and by C. Hulse and R. J. Sarjant on "Problems in Fuel Efficiency."]

Discussion on

FUEL EFFICIENCY IN IRON AND STEEL WORKS.

The following three papers were discussed jointly: "Fuel Problems in the Swedish Iron and Steel Industry," by M. Tigerschiöld; "Problems in Fuel Efficiency," by C. Hulse and R. J. Sarjant; and "Fuel Utilization in Iron and Steel Works," by N. H. Turner and F. A. Gray.

Mr. J. B. M. Mason (Ministry of Fuel and Power): Permit me to express the appreciation of the Ministry of Fuel and Power for the manner in which the Institute has devoted a large part of its programme at this meeting to the study of fuel utilization in iron and steel works. In giving pride of place to such a subject, the largest processing industry has realized the serious fuel position of the country, and the papers which have been presented are an excellent contribution. I only hope that the valuable information given is universally applied, for much still remains to be done in the efficient utilization of fuel. I should like to thank the many individual members of the Institute who have given their assistance in furthering the advancement of correct fuel utilization during the war years, and to pay tribute to the work which has been done in that connection by Mr. E. C. Evans; his ingenuity and drive have been of great value in the setting up of the new research organization and its committees.

I am sure, however, that the authors of the papers will be among the first to admit that a high proportion of the fuels now being consumed in the iron and steel industry could be saved without in any way militating the productivity of the undertakings and the quality of their products. This is the first Annual Meeting of the Institute after the successful termination of the second world war, and I am sure that every member here must be proud to belong to the British iron and steel industry, an industry which has given of its best during the war years; proud of its increasing productivity and of the number of its products; but I ask you, are you proud of the fuel utilization in your respective works?

Dr. R. J. Sarjant: No.

Mr. Mason: Thank you, Dr. Sarjant. I am sure that you are not. Much still remains to be accomplished. From the coke ovens to the finished article there are many heat leakages, and it is only by the constant attention of properly qualified men that these leakages can be traced and plugged. I should say that the iron and steel undertakings have the largest proportion of qualified fuel technologists operating at the present time, but I know that even the largest firms require more qualified men, and that undertakings of small and medium size have room for the employment of such technicians.

Research on fuel problems will receive a great impetus from the committees which have been set up. I happen to be a member of the Fuel Committee, and I have never had the pleasure of sitting on a stronger committee. I am looking forward to great results in the field of fuel utilization from the findings of that Committee, and I should like to pledge the full support of my Ministry in all the activities of your industry which are directed towards economy in the utilization of fuel.

We should welcome the establishment and development of a strong fuel department in every works, except, of course, the very smallest. Such departments would be responsible for seeing that existing knowledge of fuel utilization is properly applied, and that new problems in which research is required are brought to the notice of the Committee. Research in all aspects of iron and steel processing is receiving the attention to which it is entitled, and we are very pleased to see that in the programme of work, economy in the use of heat and power holds a very high position; but although research is of the utmost importance if the high position which the iron and steel industry has established is to be retained, I should like again to emphasize the necessity of applying in all your works the wide knowledge on fuel utilization that already exists. That, in a very short time, would itself make the industry as a whole much more thermally efficient.

I know that you have heard all this before *ad nauseam*. I am not gifted with great powers of rhetoric, and therefore cannot correctly stress in words the importance of the subject; but I know that unless we direct our united efforts to the saving of all classes of fuel during the next two years, we shall not continue to maintain our position as one of the greatest nations in the world. We have built our success as a nation on coal, and we can hold that position only by using coal skilfully and well. The fuel position is becoming critical. Coal stocks have shrunk from 10,000,000 tons to 6,000,000 tons during the course of the last twelve months. They are still shrinking and will continue to do so unless we quickly stop our extravagant fuel usage. Plant conversion to oil fuel will help, but it will not be until the late autumn that the stocks of oil in this country will be sufficiently built up to enable industry, and especially large consumers such as yourselves, to change over a proportion of your plant to oil.

No heat wastage is too small to ignore. The papers have very rightly emphasized the importance of paying close attention to fuel utilization in the finishing departments, because it is there that extraordinary savings can be effected. During the war years your industry was faced with the utilization of strange fuels—but not half so strange as those used with equanimity in Sweden. You may feel, however, that major savings could be made if your undertakings could be supplied with more consistent and better qualities of fuel as regards both cleanliness and grading. My Ministry, of course, have not lost sight of this fact; we could not do so, for we are continually being reminded of this aspect. As the position becomes more normal we shall strive to make available the correct fuel to suit the specific purpose for which it is being used. This is necessary if we are eventually to achieve the highest processing efficiency.

Dr. Sarjant, in his paper, and Dr. Desch, in his Presidential Address, have rightly emphasized the importance of education in our forward planning. Dr. Sarjant, as Chairman of the Ministry's Education Sub-Committee, knows of the vast amount of work which has been done during the war years, but I am afraid that only the surface of the problem has been scratched, because managements are not providing the incentive that is necessary. You are the people who can make these plans of ours come to fruition.

Technically, I should like to see more research work on gas producers. Taking the country as a whole, if you examine the gas producers you find that their average hot-gas efficiency is 70%. The iron and steel industry uses 6,000,000 tons of fuel per year in its gas producers. I do not see why the hot-gas efficiency of gas producers should not be raised to 90%, which would mean the saving of 1,000,000 tons of coal.

Dr. Sarjant made an important reference to taking out thermal balances for the whole of your undertakings. It emerged strongly in the war years that it was not possible to achieve thermal efficiency in any undertaking, whether a large integrated iron and steel works or a humble laundry, unless one could discover where the heat was being absorbed. It is necessary to establish some kind of "bogey" or standard, so that actual practice can be compared with what can be achieved. I suggest that there is great room for a travelling team, or teams, of qualified fuel engineers charged with the task of obtaining thermal balances for the various undertakings. The teams could travel the country in motor vans complete with instruments, and make prolonged visits to works in order to assist the resident staff.

In conclusion, there are one or two points which I should like to emphasize: It is necessary to see that your old and new plants are correctly integrated in order to achieve an overall thermal efficiency; that your new plant is fuel-worthy; that your entrants, both executive and operative, are trained to appreciate the plant which you provide, and that they will operate it skilfully so as to obtain production efficiency with fuel efficiency.

Mr. G. Doxey (Messrs. Stewarts and Lloyds, Ltd., Corby): I feel that the Institute should be very gratified by the extremely high standard of these papers and the very wide field which they cover. The obvious reaction to Dr. Tigerschiöld's paper is that it makes some of our problems look very simple. To effect such a complete change in fuel and at the same time to increase output and efficiency is a very notable achievement. I feel that there are many lessons to be learned from the paper.

The use of metal recuperators instead of regenerators for blast heating is noteworthy. I should like to ask Dr. Tigerschiöld what is the life of the elements in these recuperators and what is the method of controlling the blast temperature. The method with the ordinary stove is to heat the blast up to a higher temperature than is required, and then to dilute it with cold air to the desired temperature; but it seems possible that the temperatures obtainable in recuperators may be such that there may not be that margin of temperature which permits dilution. Is the blast temperature controlled by controlling the amount of gas burnt in the recuperator?

Dr. Tigerschiöld: Yes, that is what we do.

Mr. Doxey: Can you give us any idea of the sort of temperature control which is obtained, how steady the temperature can be held, and how far it is affected by any variation in the calorific value or pressure of the gas, or the amount of blast which is taken by the furnace? Do you control the temperature automatically, or is it hand-controlled?

Dr. Tigerschiöld: Both. We can control the temperature within about 10–15° C. without any difficulty, and very often we do it automatically.

Mr. Doxey: The paper by Mr. Hulse and Dr. Sarjant is a masterly survey of up-to-the-minute trends in fuel engineering. Table IV. is of particular interest in bringing out clearly the fact that steady conditions are hardly ever established at any time in any sort of furnace which works the ordinary five-day or six-day week. In view of this it is to be hoped that the authors and their collaborators will carry forward their method of

machine calculation to the fullest possible extent, so as to provide approximate solutions for all common types of heat-distribution problems, both in furnace structures and in the material heated. There is still a great deal of scope for development, and similar extensions of the available data on heat transfer in particular cases are also urgently required.

I should like to add one or two items to the list of investigations which might be carried out: There is the question of burner design from what might be called an aerodynamic point of view. This is closely tied up with similar problems in the furnace, but I have not come across a great deal of work on the aerodynamic aspects of burner design, and I think that such work might be very beneficial. The basic principles of the design of gas-cleaning units might also be studied a little further. There is a possibility of making simpler, cheaper, more efficient, and more compact units.

In connection with instruments, I would make a plea for reasonably priced oxygen recorders for the control of combustion in cases where the measurement of CO_2 does not give the information desired. Some instruments already exist, but as far as I know there is not a great deal of experience of them at the moment in this country. In this, as in other instrument and regulator questions, I think that much might be gained by closer co-operation between the industry as a whole and the makers of instruments and regulators, and I feel that it is for us as an industry to make our requirements quite clear and precise, and to give all the help possible in producing the instruments that we need. Contacts could also profitably be made with certain other interests, such as the chemical industry, where somewhat similar problems exist.

The paper by Messrs. Turner and Gray is a very able exposition of the advantages and of some of the complicated problems of interconnected blast-furnaces, coke ovens, and steelplants. The authors are to be congratulated on the very clear way in which they have set out the possibilities of heat conservation in works of this type, and the careful planning which is called for if the possible savings are to be achieved. There are one or two points in connection with that development which I should like to emphasize, not in any way criticizing what the authors have said, but bearing out points which they make in their paper.

Generally speaking, works in which the only fuel imported is the coal for the coke ovens, and in which all the heating is done by by-product gas, must waste a considerable amount of the latter. Neither production nor consumption is constant. Minimum production must cover maximum consumption if expensive heat delays are to be avoided, and at all other times there is a waste of gas. That is why it is so essential to have buffer consumers. For maximum flexibility these should be of two types: (1) Those in which blast-furnace and coke-oven gas are interchangeable, and (2) those in which either or both of these fuels can replace a third imported fuel so that every scrap of by-product gas which can be saved effects a direct saving in the imported fuel. Coke ovens are the best example of the first type, and in this connection the conception of them as "heat transformers" is a most valuable one. Boilers are the commonest example of the second type, but power generation may also be an important buffer in cases where power is also purchased from the grid, purchased power being, of course, equivalent to imported fuel. Coke-oven gas-holders fulfil a somewhat similar function, although the cost of storing the usual large week-end surpluses would be, in many cases, prohibitive. A question which might well be considered from a national point of view, is whether the external sale of these very large quantities of surplus gas could not be made attractive. This point may be of interest to Mr. Mason.

Blast-furnace gas-holders can never be made large enough to have any appreciable heat-storage capacity, and their main purpose is to provide adequate time for alternative fuels to be substituted when blast-furnace gas becomes scarce, and to damp out momentary fluctuations in supply.

Tar is also a very valuable by-product fuel—in open-hearth plants it is one of the best of all fuels—but it is in a different class from the gases on account of its greater ease of storage and transportation, and its value as the basis of the coal-tar industry, which open up a wider market for its sale. There are thus fewer difficulties in the disposal of tar, and any surplus can usually be sold profitably. Increases in the market value of tar and its products might even make it economic to use coal, and to sell or process the tar.

It is worth noting that there is more than a possibility that developments in the chemical industry may increase the value of coke-oven gas in a similar manner.

I now come to a point which seems to me to be of fundamental importance. The authors very rightly point out that future economies in blast-furnace practice may lead to much smaller quantities of heat in the form of blast-furnace and coke-oven gas being available. It cannot be too clearly realized that the full benefits of this saving can only be attained if the heat requirements of the rest of the works can be correspondingly reduced, so that reductions in the coal requirements of the ovens do not lead to increases in those of other departments.

Now, in the greater number of integrated works, fairly efficient use is already made of by-product

fuels, and the mere application of up-to-date fuel-engineering technique to existing units is not going to be enough to enable demand to be reduced in proportion to production. Plant will have to be modified or, where necessary, rebuilt to make the best possible use of whatever fuels are available and, in addition, a very wide survey of the whole steelmaking process must be made, and all sources of waste heat, *e.g.*, heat in slag, in coke, in blow-gases from Bessemer converters, and in steel, &c., must be tapped. The heat in the coke is sufficient to supply all the live-steam demands of the coke-oven department; and the heat in the gases from the converters, if it could be economically utilized, would be much more than sufficient to supply all the steam for the Bessemer department.

Power economy has also to be considered. It is probable that future developments in rolling and in plant layout may lead to considerable reductions in the power requirements of mills. In this connection the possibility of major changes, such as the continuous casting of semi-finished material (billets, strip, &c.), which might cut out the gas requirements of soaking pits and reheating furnaces and a great part of the power requirements of the mills, should not be ignored. Some metallurgists may have something to say about the possibility of increased use of the thermally economical Bessemer process.

Suggestions such as these are perhaps rather revolutionary, but Dr. Tigerschiöld has shown that great changes in practice can be carried out under the urge of necessity, and bold measures are called for if the future is to be faced with confidence.

It is evident that the fuel engineer must be in a position to take a very broad view of his work. He should be in very close touch with his management, and should have access to all necessary costs. And, finally, as he will have to devote so much of his time to development work, it is evident that he will need to have such staff at his disposal as will enable him to get the routine work carried out with the minimum of personal attention.

Mr. H. C. Armstrong (Messrs. Thos. Firth and John Brown, Ltd.): I consider it a very great compliment, as a visitor, to be asked to come to this meeting and take part in the discussion. If I can leave you with a healthy dissatisfaction with present conditions, I shall think that I have repaid the compliment. To my mind, this is a tragic occasion; it is surely a tragedy that after the worst war that the world has ever known we should have these troubles coming from another source. We are not getting the coal and we are not going to get it. Mr. Mason has referred to the necessity for a "bogey." We have one: In 1939, we produced 231,000,000 tons of coal; last year we produced 174,000,000 tons. That is a drop of 57,000,000 tons, or 25%. We are exporting to-day 3,000,000 tons, but we should be exporting, on a pre-war basis, 33,000,000 tons. This is a national matter. The steel industry is national, but coal is national to everybody. You have all to try to save 25%; that is your bogey.

Messrs. Turner and Gray tell us that everything they are doing is very good. Well, they have to do better. Dr. Sarjant is more honest. He and I know that we are both doing very badly, and that we have plenty of scope for improvement. Managements, however, are not yet fully alive to the problem. We must have a re-orientation of our ideas, and bring fuel into every question.

I know that one way of proceeding is to get more out of a furnace, but I call that works management; that is not fuel efficiency from the point of view of the fuel engineer. We have to do something more to save our fuel. I have been in the fortunate position during the last three years of seeing every single iron and steel works in the Sheffield and Rotherham districts, representing a consumption of something like 2,000,000 tons of coal per year. I know the sort of saving that is possible, but it cannot be done until you wake up and realize that you cannot have anything that you like to ask for from your purchasing department. You cannot simply ask your purchasing department to provide you with so much coal and think that you are going to get it. Mr. Mason has warned you that you are not going to get it. In any case nature is not going to provide us with such good sulphur coals or with quite such high fusion points as we have had before. We have to face these facts and do something quickly.

I have said that this is a tragedy. Is it not a tragedy that a man like Dr. Sarjant should have to say "I told you this 20 years ago"? I have often disagreed with Dr. Sarjant, but I have never agreed with him more than since reading his paper.

It is no use complaining about you without telling you what to do. One thing which you should do is to take the paper by Mr. Hulse and Dr. Sarjant away with you. Works managers, fuel engineers, and furnace managers are all interested in this subject and they should study every line of the paper, and ask themselves whether they are doing what is recommended in it. There is enough in the paper to keep you busy for the next 12 months.

The paper mentions air/fuel ratio and under-feed stokers. I believe that the mechanical stoker has a very great future. It is a lazy way out to say that you will use gas. Moreover, the gas is not available. Coal has the highest and

most concentrated heat units and, if we know how to use it, it is our finest fuel. The mechanical stoker is progressing. Control of the coal/air ratio is being practised to-day and is giving 25% economy on top of that obtained by mechanical stokers. It is not enough merely to instal a mechanical stoker; control of the coal/air ratio is essential. I have even seen stokers with the air inlet choked. The air/coal ratio is very important.

My own experience of pulverized fuel is slightly disappointing. I am a great believer in it, but we need help in overcoming the difficulties of the lighting-up period. During that lighting-up period a partial low-temperature carbonization takes place; incomplete combustion results, the "smoke" being fine coke which blows on to the crane tracks, &c. Under the microscope, it can be seen to have a coke structure, and if it gets on to your machinery and cranes, &c., it grinds them to pieces. It is the lighting-up problem with pulverized fuel which causes the trouble and makes engineers want to get rid of it.

On p. 169 P of their paper, Mr. Hulse and Dr. Sarjant refer to rates of heating in furnaces. Dr. Sarjant has done a great deal of valuable work on that subject. Those who look after heat-treatment are rather like chemists; they cover themselves in a miasma of technical terms, and they exaggerate their temperature-time to be on the safe side when it is unnecessary to do so. There is great need for you to consider this heat-treatment question and to come to a definite decision as metallurgists about what is really necessary. I ask you to examine what Dr. Sarjant has to say on this subject, because I think that there is no doubt that we are overdoing our heat-treatment.

The authors also mention coke. If any of you have to handle coke, I advise you to look out for sulphur. Do not forget that sulphur is acid, and that you must watch the pH value of all your washing water, or you will be in trouble sooner or later.

The authors also refer to the gas ratio with town's gas. If you know the speed-of-combustion rate for town's gas, you will appreciate what your air/gas ratio means. I can go into most works that use producer gas and see the furnaceman turn the gas up or down to alter the temperature, but he never touches his air from one week-end to the next.

Pipe-fitting and engineering is frequently poor. You get a clever man in to design a plant and a wonderful man to work it, yet you leave it to the pipe-fitters to put up the most convenient pipes they can, and find that you have 30 or 40 burners to alter, with a large number of taps, when you ought to have one main control for the air and one for the gas. Those are the little ways in which you ought to be able to make this necessary saving of 25%. Previously these things have been left to someone else, but now you will have to deal with them yourselves.

With regard to waste-heat boilers, I suppose that these are advocated by fuel engineers more than anything else, and are more disliked by the average manager than anything else. I am not referring to the melting-shop boiler. Is it not a question of psychology? Under the law, a boiler must have an attendant, and if you see this man doing nothing you do not like it. The engineer says, "this boiler is down for inspection next week, and I want the furnace," and you reply "these waste-heat boilers are a nuisance." Recently I came across a case where the boilers were definitely very inefficient as boilers. The firm in question were getting 9% of the heat from the coal into the steel to heat it, yet they were getting 9·2% of the heat into the water. They could have done a great deal better; you can easily get 15% with an ordinary boiler.

Many forge managers are not concerned with their waste-heat boilers but only with forging steel. It is, however, their job to use the steam from them and to use the heat in the steam. I should like your fuel engineer to tell you continually what percentage of your heat you are getting into your steel and what percentage you are getting into your steam. You should be just as interested in the heat in the steam as anything else. You must forget this term "waste heat." Speak of "heat wasted" if you like, but not of "waste heat." I have asked people why they do not lag their waste-heat boilers, and they have replied, "why should we? They are waste heat."

I think the most important fact for us which emerges from Dr. Tigerschiöld's paper is the fact that people in Sweden have so much belief in preheat. I should welcome it if under nationalization a law was brought in to say that no one should be allowed to put a clean gas furnace into a works without recovering the heat. Think what is being done all over the country: A burner is put into a box and it is called a furnace! You ought to be made to recover your heat from gas, whether you make it yourself or buy it.

There is one statement in the paper by Messrs. Turner and Gray which may be misleading. They say on p. 189 P that it is possible to convert a furnace from coal to gas with a saving of up to 50%. Why? Is it not because the coal furnaces are the furnaces put in two generations ago, furnaces with no insulation, furnaces which are just thrown together? Then you put in a modern gas furnace with insulation and proper controls and instruments, and you say that you are saving 50%. It is not right that all that credit should be given to the new furnace, when the coal furnace has been neglected. Coal is under a cloud, but it can be extremely useful.

I do not agree with what Mr. Mason has said about the training of our men. I take off my hat to the man with the shovel. Think of the rotten apparatus that we have given to the furnacemen! What they can do with a shovel is astounding. I am not at all sure that the education of the furnacemen should come from the Government or from any college; I think that it ought to come from the manager.

Fifty years ago, just before I left school, all my boy friends were going to become electrical engineers. To-day, electrical engineering occupies a very high place. I hope that in much less than fifty years' time fuel engineering will be recognized as being just as important. The fuel engineer is needed; he has to be trained, and then the job is there for him. If you do not have him you will fail, because you depend on coal absolutely.

Mr. M. W. Thring (British Coal Utilisation Research Association): This discussion and the paper by Dr. Tigerschiöld seem to me to bring out clearly the fact that there are two quite different ways of making progress in an industry. One is by steady and continuous progress, and I hope that our work with the heat-flow meter and the work which has been done on port design with The United Steel Companies, Ltd., may play some part in that. The second way may be called a "quantum jump," *i.e.*, a big change with something new coming into the industry. That kind of quantum jump occurs when the gap between technical knowledge and actual industrial practice, to which Dr. Sarjant referred, becomes too great, or, alternatively, as in the case of Sweden, when the economic situation changes so drastically that it is simply forced upon the industry. Two great examples of the quantum jump were the introduction of the Siemens regenerative furnace about 80 years ago—Messrs. Turner and Gray refer to the fact that there have been no great changes in design since then—and the change from the old beehive oven to the coke-oven battery.

Certain quantum jumps of the second kind seem to have been forced on Sweden by the war situation, but a still more important point is that the advances to which Dr. Tigerschiöld refers may clear the way for even bigger jumps. The preheating of gases to 1000° C. in a continuous preheater, to which he refers, opens up enormous possibilities. For example, a direct-fired open-hearth furnace becomes economic if the preheat temperature with continuous preheat can be kept over 900° C. Similarly, continuous supplies of water-gas can be produced with preheats of this order. Whether that kind of quantum jump will come as a result of these changes in preheat seems to depend on the economic situation in the future.

On the general question of preheat, it is clear on thermodynamic grounds that what is needed in a continuous counterflow preheater for high temperature is different designs for different parts of the preheater, and the INKA preheater is a step in that direction. I should like to ask Dr. Tigerschiöld why it is not built with the convection preheater behind it, as in the radiant-tube boiler, instead of separating the radiant unit from the convection unit. There is a very close analogy with the radiant-tube boiler followed by convection heating. I think that preheater designers and boiler designers have a great deal to show each other.

Another example of this method of designing a preheater with different arrangements for different temperatures is given in a recent Swiss patent (British Patent No. 574,810), where the diameters of the tubes are stepped down towards the hotter end, so that the tube temperature comes closer and closer to the temperature of the cooler fluid and is prevented from overheating.

I should also like to ask Dr. Tigerschiöld why the blast-furnace fuel shortage led to preheaters of this type. Was it because the efficiency could be much higher than with the regenerative type?

Dr. Sarjant referred to the desirability of a non-water-cooled heat-flow meter. A meter of that type was actually used in an open-hearth furnace in Russia in 1939, but in working on this problem which was suggested by Dr. Sarjant about six years ago, we decided that a water-cooled instrument was preferable, because it can be left in the furnace and used continuously for a long time, which is a great advantage for a research instrument.

Mr. Armstrong referred to oxygen recorders. We have used an oxygen recorder throughout the trials done at The United Steel Companies, Ltd., and it has worked quite successfully. This recorder was specially designed for the trials.

Mr. F. Kennedy (Messrs. Dorman, Long and Co., Ltd., Middlesbrough): The paper presented by Dr. Tigerschiöld describes some extraordinarily good work which has been done in order to overcome difficulties greater than those experienced on the fuel side in this country. Apart from expressing my appreciation of this performance, I have no general comments to make, but should like answers from him on the following minor points:

(*a*) What was the calorific value of the blast-furnace gas with a coke consumption of 13 cwt.?

(*b*) The quoted thermal efficiency of the recuperative hot-blast heater is decidedly lower than can be obtained with normal stoves packed with refractory checkers; many of the

latter type of unit in this country are running at efficiencies in the neighbourhood of 90%. Are any other operating advantages obtained with the recuperative heater which offsets its lower thermal efficiency?

(c) When blast-furnaces are operating in conjunction with an associated steelworks, would it not be preferable to use the blast-furnace gas for metallurgical heating furnaces instead of for steam raising, as substitute low-grade fuels can more easily be supplied to boilers than to metallurgical furnaces.

I should like to deal with one or two points raised by earlier speakers in the discussion.

Mr. Mason suggests that a million tons of fuel per annum can be saved by improved gas-producer operation. I question the accuracy of this statement. There may be occasional small plants where producer efficiencies are as low as the 50% he quoted, but the bulk of the coal used in the industry is gasified at the larger works where the hot-gas efficiencies obtained are much closer to 90% than the values mentioned by Mr. Mason.

Mr. Armstrong's opening remarks regarding the paper by Messrs. Turner and Gray are in his usual provocative style which he invariably adopts to liven up the discussion; however, I am not in agreement with him, but consider that it is an excellent paper. The authors record what is being done in two plants of rather different types and their comparison emphasizes clearly two different aspects of the fuel-economy campaign in the industry:

(1) The thermal efficiency of each individual fuel-consuming unit must be tuned up to the maximum.

(2) The overall importance of integration.

The greatest thermal savings are obtained by operating completely integrated plants in which the finishing processes are completed on the one site without allowing the material to get cold in any of the intermediate stages.

The improved efficiency obtained by conserving as far as possible the heat available in (1) the molten iron from the blast-furnaces, (2) the molten steel from the steel furnaces, and (3) the semi-finished material during the various rolling processes greatly outweighs what can be done by improving the efficiency of any one individual heat-consuming unit.

The data and comparisons supplied by Messrs. Turner and Gray demonstrate these advantages of integration very clearly.

In view of the earlier remarks in the discussion, I suggest that the authors should elaborate what they consider to be the functions of the fuel engineer. There appears to be an impression in some quarters that the job can be regarded as a water-tight compartment, whereas my experience is that his job is *the* one on the works which cannot be run as a water-tight compartment; to function successfully, the fuel department must work in close co-operation with the designing, engineering, metallurgical, manufacturing, and accountancy departments, and to get the best results it must be considered part of the team and operate in such a fashion that it is practically impossible to define clearly exactly where the fuel engineer's duties begin.

The very large reserve of gas-holder capacity which is being installed to work in conjunction with the Orgreave plant is an indication of the importance attached to obtaining an optimum efficiency from the use of coke-oven gas. The large reserve capacity installed should ensure that the point of usage of coke-oven gas is solely dictated by the efficiency and suitability for that particular process, whereas when gas-holder capacity is small, the consumption must be so organized that in case of marked variations in supply or demand, the coke-oven gas can be substituted by, or used as a substitute for, alternative fuels.

I should like the authors to discuss a little in detail the reasons which lead to their proposing to instal a total of 9,000,000 cu. ft. of gas-holder capacity to deal with the coke-oven-gas output from the Orgreave plant, as I am sure these would be of considerable value to many other interested parties.

I do not favour the arrangement of the gas distribution so that the open-hearth plant is fired with a mixture of blast-furnace and coke-oven gas. This practice has not been entirely successful and considerable trouble has been experienced with slag foaming and the obtaining of a flame with suitable luminosity; therefore, my own recommendation is to organize the distribution so that the open-hearth plant is fired with coke-oven gas only, which, however, usually necessitates the use of blast-furnace gas for firing the coke ovens.

A point is made in the paper by Mr. Hulse and Dr. Sarjant that coal is the industrial fuel which we have to use at present-day prices. Suitable coal for gas producers costs a minimum of 46*s*. per ton, to which must be added a gasification cost of 5*s*. or more per ton and in these circumstances oil becomes an important competitor. The oil-fired furnace is capable of a decidedly better overall thermal efficiency than the producer-gas-fired unit, and in many cases where high temperatures are required, such as at the open-hearth furnace, the additional increase in output which can be obtained from a given unit adds still further to the advantages of oil firing. Thus,

even at the present time, many knowledgeable people have decided that the use of oil fuel will give a lower operating cost than coal gasified and, if the high war-time oil prices are reduced, the competitive attack of oil will be still greater.

Mr. G. A. Young (Messrs. Richard Thomas and Baldwins, Ltd., Ebbw Vale): I was very pleased to hear Mr. Mason refer to the quality of coal. Much intensive work has been done on fuel efficiency and we hear a great deal about it, but I submit that on the present basis of a fixed price, irrespective of the quality of the coal, there is no encouragement for the coal supplier to keep out shale, and in consequence supplies are becoming increasingly dirty.

It is obviously wrong that a coal supplier should be paid for shale at the price of coal.

Reference has been made to open-hearth furnaces as the largest consumers of fuel, but blast-furnaces are the major users of solid fuel, and so an improvement in the quality of coking coal would lead to a considerable saving of coal.

Cleaner coal would result in:

(*a*) Better coke from the point of view of the physical characteristics.

(*b*) More carbon per ton of coke.

(*c*) Less limestone for fluxing the reduced percentage of ash in the coke.

(*d*) Less coke for melting the reduced quantity of slag.

(*e*) Less slag to handle.

(*f*) A higher output of hot metal and a lower coke consumption per ton of hot metal produced.

Thus, in this way a considerable saving in fuel could be effected.

I suggest that the time is long overdue when coal should be sold on a calorific value or on an ash basis. The accumulative benefits that would accrue to the iron and steel industry from cleaner coal would enable the price for the higher grades to be fixed at a level at which it would pay the coal supplier to pick out the shale on the picking belts and to wash the coal more efficiently.

Under the heading "Effect of Irregular Working of the Blast-Furnaces and of Future Developments in Blast-Furnace Practice" Messrs. Turner and Gray have drawn attention to the fact that the extended application of ore beneficiation is likely to influence the quality and the volume of the blast-furnace gas. This extended preparation of materials outside the blast-furnace should include coke; more uniform operation and a more uniform gas make would result.

Besides reducing the effect of the fluctuations (to which the authors refer) during periods when it is necessary to change tuyeres, &c., the large gas-holder maintains a uniform gas pressure at consuming points. Uniform gas volume, uniform gas quality, and uniform gas pressure are the essentials if maximum fuel efficiency is to be maintained.

I should like to emphasize what the authors have said with regard to central gas control. I particularly refer to those large integrated iron and steel works where a considerable time is required to get from one end of the works to the other. For such works it is essential to have a central station from which it is possible to control the distribution of the gases. The volume of the gases distributed is so large that the working margin available in gas-holders is very limited, which makes centralized control necessary.

With a large gas-holder floating on the distribution system there is danger of filling a building with gas if a leakage or a fracture in a gas main inside a building is not speedily noticed, and it is most essential that someone should be on the alert to spot any abnormal condition at a very early stage. An important duty of the gas-control-station attendant, therefore, is to balance gas consumptions against the gas make, and this should be done hourly or half-hourly. The figures will, of course, be uncorrected for changes in temperature, pressure, and specific gravity—this can be done later—but the figure that is not accounted for will serve as a useful guide and will give an indication of conditions throughout the works.

On the question of balancing gas consumptions against gas makes, I would strongly advise that all consuming points should be metered. It is sometimes the practice to leave one consuming point, for example, the boiler plant which takes the swings in gas supply, to be arrived at by difference. It is important to close the system of metering so that errors in metering can be immediately shown up and the offending meter or meters tracked down.

The authors have drawn attention to the important function of the gas-control station in controlling the distribution of the gas to the best advantage and, in cases of partial failure, in according priority of supply to particular units, so that the gas available can be used to the best advantage. That is most important; but it may not always be realized that it is just as important to control starting up as to control shutting down. For quick and efficient control, rapid communication between the central gas control and the gas-producing and gas-consuming points is essential. A useful investment is an automatic signalling device by which a signal may be given either by coloured lights indicating whether blast-furnace or blast-furnace and coke-oven gas are to be reduced or shut off; this may also be done by means of a loudaphone. If holder-level

indicators are installed at gas-consuming points it is possible to arrange beforehand the routine for shutting down at once in an emergency.

A further step towards obtaining maximum fuel efficiency in a large works would be to introduce a system for metering steam, and for balancing consumption against make, in the same way as for gas.

Reference has been made to meter maintenance, and this is very important. I think it is essential to have a good workshop for meter maintenance and calibration. Furthermore, it is of paramount importance that the workmen should be specially trained for the work; it is not the job of an ordinary fitter or of anyone who happens to be available. Men must be specially trained, and this takes a long time. Unfortunately, suitable men are difficult to find at the present time but this phase will pass.

Mr. T. F. Pearson (Messrs. Colvilles, Ltd., Glasgow): I would like Dr. Tigerschiöld to tell us the analysis of the producer gas made from straw. Presumably it was of poor quality and would compare unfavourably with our normal producer gases which are enriched by tar vapours and soot. The point is of some importance since, when we speak of thermal efficiency, we are apt to forget the effect that the gases used may have on this value. Any furnace, no matter how good, is handicapped if the fuel used in it is poor. Messrs. Turner and Gray emphasize this by speaking of coke-oven gas as a "high-grade heat" source because the inerts are low, and when we consider blast-furnace gas containing 60% of nitrogen burning with air containing 80% of nitrogen then obviously the amount of inert gas put through the furnace does prevent the achievement of highest efficiency.

A point of interest in the paper by Mr. Hulse and Dr. Sarjant is raised when the authors state that the effect of varying saturation temperatures is to achieve an optimum performance which falls away on either side of a certain value. This was noted as early as 1909 by Gibson and Gwyther * and the explanation appears to be in the general characteristics of the steam–air–carbon system. We have recently been studying producer-gas reactions over the whole range of blast compositions from 100% steam to 100% air. Fig. A illustrates results for a fixed set of conditions, *i.e.*, temperature and driving rate. At the extreme left is the equivalent of the "down blow" in a water-gas producer yielding some 48% of hydrogen and 40% of carbon monoxide, and at the extreme right 100% air has been used as blast. The curves showing the change in composition of the gases with different H_2O/air proportions are interesting, particularly those for CO and CO_2.

If the range between the dotted lines is chosen it is found that the change in concentration of the various constituent gases agrees reasonably well with this early work on the effect of varying the saturation temperature, which showed that, as the moisture content of the blast is increased, the CO content falls, the CO_2 content increases, and the H_2 content increases and then falls slightly. The results obtained recently deviate here, since our curves show the H_2 to increase continuously under all conditions.

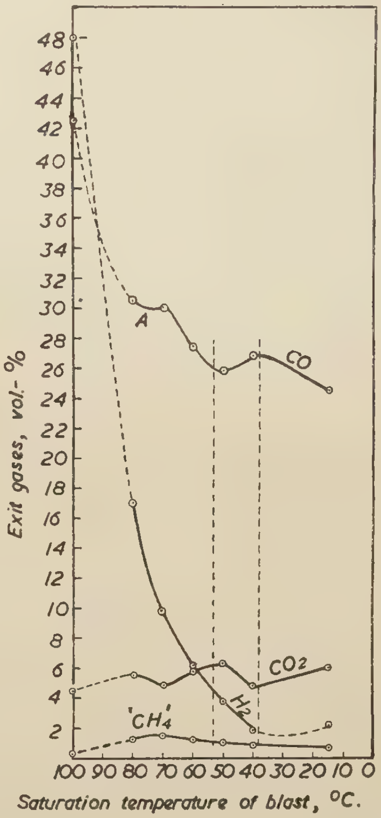


Fig. A.—Variation of Composition of Exit Gases with Saturated Temperature of Blast.

One significant point arises, however, in that there appear to be two minima in the CO curve, the second, at *A*, fitting in better with the H_2 contents of actual producer gases, *i.e.*, 11–13%. If this point *A* is within the working range in practice, then the effective saturation temperature of the blast reaching the incandescent zone is greater than that normally suggested by external measurements. Hence it is tempting to suggest that we do not get a true measure of the H_2O reaching the fire, and the reason may be

* A. H. Gibson and R. D. Gwyther, *Proceedings of the Institution of Civil Engineers,* 1909, vol. 177, Part III., p. 264.

that in the usual water seal producer, in addition to the blast moisture, there is a considerable evaporation through the hot-ash bed by capillarity and radiation, the fire actually running at some saturation temperature which is appreciably above the usually accepted range of 50–60° C.

Dr. R. Durrer (Switzerland): I should like to express my thanks for the opportunity of taking part in this meeting and for the kindness I have received during my stay in London. We Swiss, with our small iron industry and our small country, are, of course, not only interested in all the problems which are discussed here, but also in coming into touch with your big iron industry, after having been cut off from the world for some years.

Coal, next to iron ore, is the most important material for producing iron, not for any one particular country, but for the whole world. And it is not only metallurgists that are interested in discussing the problems of fuel economy; it is everybody's duty to save fuel wherever possible. From this point of view I am pleased that this world-wide necessity should be dealt with at this meeting, and particularly so, that the problem of using concentrated oxygen in producing iron and steel has been mentioned in one of the papers, because by this method enormous quantities of coal may be saved.

I am told that some weeks ago the Russians announced their intention to intensify the use of concentrated oxygen in the production of iron, after having dealt with this method for many years. It is surprising that the other iron countries do not attach the same attention to this idea.

As far as I know, the Russians have used until now oxygen of a concentration up to 70% for smelting iron ores, but, according to the reports I have got, they did this work always in an ordinary blast-furnace, whereas I think that the greatest advantage from the use of concentrated oxygen will be the possibility of reducing the height of the furnace from about 30 m. to only a few metres.

Enormous quantities of fuel could be saved not only in the smelting of iron ores but also in oxidizing pig iron. In using concentrated oxygen instead of the usual blast, more than half the world's scrap iron could be melted with the heat saved by this kind of working, and by further changes in the combination of smelting and steelmaking, all the world's scrap iron could be fused in the converter, so that the open hearth would lose its principal task.

I should be happy if these ideas could lead to a more intensive treatment of the question of using concentrated oxygen in smelting and in steelmaking, as I am convinced that this method would put our production of iron and steel on a new basis and, besides other considerable advantages, would result in a big saving of fuel.

JOINT CORRESPONDENCE.

Dr. E. S. Grumell (Imperial Chemical Industries, Ltd., Winnington, Northwich; Chairman, Fuel Efficiency Committee) wrote: As Chairman of the Fuel Efficiency Committee I should like to say how very much we appreciate the fact that such a large proportion of the time of this important meeting has been devoted to fuel efficiency. It is hardly necessary for me to stress the importance of this subject in view of the continued shortage and high price of fuel. I consider that the presentation of three such excellent papers at this meeting indicates the great advances in knowledge which are being made and a very definite attempt to bring them before all the members of the iron and steel industry.

I have read these three papers with great interest, and should like to mention the following points:

Turner and Gray refer to future developments along the lines of more extended application of ore-beneficiation processes, and also to the use of oxygen-enriched air, whilst Tigerschiöld discusses the use of direct firing instead of producer gas—a change which has been successfully made in the chemical industry of this country during the war. Both Turner and Gray, and Tigerschiöld discuss the use of highly preheated air or gas and the increasing use of recuperators made of heat-resisting steel, and Hulse and Sarjant refer to the use of permeable refractories and to the high rates of heat release being obtained in America with almost phenomenal results.

Hulse and Sarjant discuss the advantages of mechanical stokers over hand-firing and show that sections of the industry are fully abreast of advances in this direction. At the same time Turner and Gray state that open-hearth furnace design has not fundamentally changed since the introduction of the process and that there is considerable scope for basic research in this connection.

With regard both to research and to practical application, their paper shows how very complicated the problem is when considered as a whole, and it indicates that there is still much to be done in spite of what has been done in the past. In this connection I may perhaps be allowed to stress the importance of providing frequent

opportunities for experts to get round a table and thrash out not only the continued application of present knowledge, but also the lines of research which should be followed in the future; and it is equally important that full information should be obtained as to progress in other countries such as America and Sweden.

It is quite evident from the papers presented at this meeting that developments of major importance are pending which require team-work and a concerted effort on the part of everybody. Moreover, these developments must be achieved fairly quickly. It is to be hoped that in spite of everybody being so busy with day-to-day problems and troubles, time will be found to follow up on a large scale the many points raised in these stimulating papers.

Mr. R. Whitfield (Incandescent Heat Co., Ltd., Smethwick, Birmingham) wrote: The paper by Hulse and Sarjant is very important and should be co-related with the recent papers on the same subject given over months past by the Institute of Fuel. Some of these papers and this one in particular should be in the hands of all furnace users.

The term "neutral atmosphere" is still used as a possibility but in reality such an atmosphere is impossible from the combustion of natural fuels. Highly superheated steam is bound to be produced from any fuel containing hydrogen; and, by its presence, CO_2 with N_2 are made active decarburizing agents. Decarburization is more damaging to steel than scaling, as the reduction of carbon alters the characteristics of the steel. It is possible to produce a practical atmosphere in which the scaling keeps pace with the decarburization.

The variation of atmosphere with hand-firing is certain and the apparent solution is the mechanical stoker. But it is a very open question as to whether the underfeed type is the best for metallurgical furnaces. Broadly speaking, it seems that an overfeed type is the best. It is an old, but true, saying, "Give me a 'soft' atmosphere from a long flame coal". "Soft" and "hard" flames can best be described thus: The "soft" flame generally has an indeterminate boundary, *i.e.*, it is fuzzy on the edges; further, the colour varies from a dull white to red. The "hard" flame has definite boundaries and is of more uniform colour which may be very bright red or white.

The great difference between underfeed and overfeed is that in the first case the air is forced through the fuel, whereas in the overfeed the principal air is introduced over the fuel; and it has been shown in practice that decarburization and scaling are more prone to occur from the underfeed than from the overfeed type. There is an important place for the overfeed stoker in metallurgical practice.

With reference to pulverized coal, the authors are quite right about the ash problem. The best results are to be obtained from the best fuel, however used, but fuels with increasing percentages of ash are now being used and will continue to be used in increasing quantities. It is quite common to use pulverized coal with 15% and even 25% of ash; the control and disposal of this ash is difficult, and trouble results from ash being rolled into the materials, apart from the nuisance of flues that are reduced in area or even blocked.

Difficulties in ash control increase with the attritor impact type of mill, from which the size of the particle can vary considerably with hammer wear; the speed through the furnace chamber is generally reasonably constant and the time comes when the ash is deposited in the heating chamber instead of in the flues. The constancy of grinding gives favour to the ball-mill type of pulverizer for this reason.

For metallurgical practice the oxygen indicator and/or recorder serves a better purpose than the CO_2 indicator. Each fuel has a definite CO_2 content for complete combustion and this varies considerably with each fuel; oxygen, in particular, requires to be controlled and is a better indicator of atmosphere than CO_2. It is equally important to determine CO, whereas oxygen determines them both with reference to the atmosphere.

Some definite contribution towards fuel economy can be made by holding elementary classes within the works. One prominent company provides comfortable accommodation and a qualified lecturer, generally from their own staff, and the rule is that all examples shall be drawn from their own ground. This eliminates the "school-boy" atmosphere; the men are paid for the one hour, usually betweem 6.0 and 7.0 P.M. They can leave work at 5.30 P.M., wash, and have a snack in the canteen at a very moderate cost; they are free for the evening from 7.0 P.M. Everybody is welcome, especially the older men. This system is now being extended into other branches of the Company's activities and is proving mutually beneficial. The class or classes form a foundation for future executives, both major and minor. These works classes are not substitutes for evening classes where the knowledge imparted is general, but they show the application of general principles to the intimate problems within their employment. It is being considered whether it is good to hold these classes, especially for apprentices, during working hours; this, however, is not generally applicable to men on production.

Mr. D. Bagley (Messrs. Donald Bagley, Ltd., London) wrote: Turner and Gray refer to possible developments in blast-furnace practice taking the form of oxygen enrichment of the blast.

Following reasonably large-scale experimental research, my conclusions were as follows :

Ferromanganese.—Economies justifying the use of oxygen can be achieved. The reduction in coke consumption may be from 0·5 to 1·0 ton per ton of ferromanganese; the product yield is materially improved, and the cost of blast preheating is reduced.

Other Ferro-Alloys.—A similar result is probable but has not yet been definitely proved.

Hematite Foundry Iron, &c.—Work in Germany on the use of enriched air in blast-furnace practice, based on coke costs at less than one-third of present British figures, suggested that the return on the capital expenditure did not appear to justify the undertaking.

A readjustment, based upon coke at 60*s.* per ton, charging blast-furnace gas at 2·3*d.* per therm, and allowing 15% for capital service, is estimated to yield a return of about 21%, which increases to over 30% if the retention of the manganese in the metal features. The coke consumption declines by 170 kg./ton of pig iron, the gas yield by 32·4 therms, and stove-gas requirements by 20 therms, so that the overall economy after debiting gas for oxygen production and crediting reduced blast power, is about 47 therms, representing a net saving of, say, 163 kg. of coke on an original consumption of 1050 kg./ton.

Open-Hearth Steel.—The use of oxygen in the open-hearth furnace seems to be a promising avenue for investigation, as a partly enriched blast-furnace gas can then be successfully utilized.

It will be obvious that the available heat in the combustion chamber, when using air enriched to 30% of oxygen, increases considerably, whilst the waste gases decline correspondingly in volume. The ultimate saving cannot be correctly indicated until trials have been made, which may necessitate some amendments in the open-hearth design as the temperature increment must be taken into account.

Theoretical considerations suggest that a saving of 40–50% of fuel can be achieved in open-hearth practice with enriched air, but the cost reduction can be substantially greater owing to the possible substitution of a cheaper gas and the elimination of the gas producer.

Only a few trials have been made on the Continent, but these were encouraging on the semi-practical scale, and should be continued here.

The separation of the gases evolved in the coking process may be of great value in the production of iron and steel, giving a choice of gases of calorific value of 1000 B.Th.U. and downwards. The isolation of ethylene—a factor of importance in future coke costs—is then practicable, and the mobility of any surplus heat in the form of rich gas is not hampered by "grids" or monopolies. Should this prognostication ensue, a radical change in the design of the coke oven is foreshadowed as two-stage carbonizing may then feature. There is no reason why the industry should continue to pay tribute for foreign oven designs; its function is to lead the world.

Dr. A. C. Dunningham (Imperial Chemical Industries, Ltd., Winnington, Northwich) wrote : There are three points in these extremely interesting and useful papers on which I should like to comment briefly; they all relate to producers or to producer gas :

(1) The need for cleaning coke producer-gas is mentioned by Mr. Hulse and Dr. Sarjant. Presumably, in the process of cleaning this gas the sensible heat is lost. In the case of gas at 700° C., this may amount to as much as 12% of the total heat in the producer fuel and is consequently well worth recovery. Do not recent developments in metallic recuperators, as described by Dr. Tigerschiöld, open up possibilities of recovering at least part of this heat which, if used to preheat the blast, would be returned to the producer and recovered in the form of gas of higher calorific value?

(2) The substitution of mechanical stokers for gas firing, as described by Dr. Tigerschiöld, opens up great possibilities of savings both in money and in fuel. A therm in producer gas costs approximately 1½–2½ times as much as a therm in bituminous coal, the former figure applying to hot gas from bituminous coal and the latter to cold gas from coke or anthracite. The demand for producer-gas firing is usually based on either (*a*) the need for clean gas, free from dust and sulphur, or (*b*) the need for close control of combustion conditions.

With regard to (*a*), present-day fuel-costs would suggest that such demands might well be reconsidered and (*b*) has in the past been based on a comparison with hand-fired solid fuel which admittedly gives irregular combustion conditions. The modern mechanical stoker, however, can often give conditions comparable to those obtained with producer gas and, in addition, combustion efficiencies of the same order.

(3) A maximum calorific value of producer gas at a blast saturation temperature of about 57° C. is recorded by Hulse and Sarjant, although calorific values are usually believed to fall with increasing blast saturation temperatures. If the suggestion made by these authors is correct, namely, that the decrease in calorific value below a blast saturation temperature of 57° C. is caused by the formation of clinker, then the application of the curve given in their Fig. 2 may quite possibly be limited to fuels possessing certain clinkering properties or to producers of certain types.

Mr. A. Stirling (Messrs. Stewarts and Lloyds, Ltd., Corby) wrote: Much of the material of the three papers and of the spoken discussion seemed to encourage a welcome shift of emphasis from fuel, as such, to the condition of the combustion gases.

The importance of the available portion of the fuel calorific value was many times recognized. In particular, Mr. Armstrong drew attention to the significance of the air/fuel ratio, so stressing once again that in high-temperature processes the most powerful diluent reducing availability is excess air.

The question therefore arises: Should not Sankey diagrams conventionally state the availability fraction of the fuel as used with the optimum value of that fraction for the process?

In assisting his executive and administrative colleagues, whose individual fuel-economy potentials generally exceed his, the fuel engineer's guidance will always be the more acceptable for being in terms of the cost of the production product rather than in thermal units.

Mr. Edgar Williams (Baglan, Port Talbot, Glam.) wrote: This excellent series of papers comprises a sound thesis for what might develop into a comprehensive symposium on the subject in our basic industry. As one who has spent the major part of a long and active career dealing with problems associated with the trade in South Wales, where the question of fuel has its own peculiarities, I would assure the respective authors that the subject matter is one which will necessarily be of general interest to all concerned. Well-merited appreciation has already been shown to each contributor, and South Wales would desire to become associated with the congratulations. We must, however, follow the advice given by Mr. Armstrong in his candid criticism, and, as he suggests, study the papers line by line in order to take advantage of the labour thus unfolded and try to discover what can be applied to our individual requirements.

In dealing with gas-producer practice, Mr. Mason stated that a 90% efficiency should be possible. He did not, however, reveal any very definite steps which might be taken to attain such desirable results. Quantities of coal have been transported into South Wales from the Midlands; experts on fuel research have been engaged from the Department of Industrial and Scientific Research, and other worthy individual investigators have been employed in past years by the Steel Association, but one yet awaits any marked improvement in the general results. What then, we ask, remains to improve gas-producer practice in South Wales and elsewhere? It is generally admitted that the problem is a real one in this district where ungraded, poor-quality fuel from local collieries reaches the plants containing undesirable ash and sulphur content and with a percentage of "fines" so high that it can hardly be credited by users in other parts of the country.

This, then, summarizes the general situation with which South Wales users are faced and such conditions are apparently being dealt with as a palliative by the Ministry of Fuel and Power by sending into the area a proportion of other and superior fuels from far-distant districts. It almost sounds like the apt phrase of "sending coals to Newcastle." After digesting the excellent contribution of Dr. Tigerschiöld, one cannot but feel, in spite of all the complaints sent forth from South Wales, that Swedish iron and steel manufacturers would welcome the asset this district possesses and quickly adapt themselves for its better use. The introduction of mechanical gas machines was largely influenced by the saving in space and the higher gasification rates made possible on the various units put down, plus, of course, the better utilization of poor-quality fuels for gas-making purposes. It is very doubtful whether coal yields per ton of steel have improved either for melting or reheating. I know, for certain, of cases where the opposite results have been sufficiently common. The higher gasification rate has all too often resulted in a gas of less-reliable quality which has been delivered over a greater distance, thus depriving it of a temperature which was once utilized at the furnace unit. Gas machines are, however, capable of being worked at higher efficiencies than generally prevail if properly controlled under well-known conditions. Bone and Wheeler, in their researches nearly forty years ago, still remain the basis for good practice.

The quality of coal is obviously much better in some districts; coal containing a high proportion of fines cannot be economically gasified at abnormal rates or in comparison with such grades as nut or cobble sizes. This, in my view, constitutes the main defect in gasifying such quality coal as so often prevails in South Wales. Its general friable nature must result in high amounts of fines being produced and there would thus appear to be reasonable ground for closer investigation into the application of pulverized-fuel installations on many consuming units now burning raw coal or poor-quality gas. The alternative will, I think, follow the direction of slower gasification, thus providing improved quality gas, but obviously necessitating plant extension as required to meet the demand. With oil fuel now being utilized to some extent on furnaces, it should be possible to work existing plants at a somewhat lower load. In any case, the necessity for greater efficiencies would, if required, justify increased gas installations in certain cases which should reduce to some extent higher maintenance costs. The quality of

fuel consumed will constitute the governing principle at each plant.

A further line for investigation might be followed by the introduction of part-waste-heat gases into the air blast. The Motala fan preheater shown in Fig. 11 of Dr. Tigerschiöld's paper, or some similar device, would appear to provide the means of dealing with the problem. This cannot be claimed as a new idea as use was made of part-waste gases in a form of Siemens reheating furnace many years ago. In the writer's experience, small ingots were regularly reheated with a coal yield of $1\frac{1}{2}$ cwt. per ton of bars rolled, and the figure of $3\frac{1}{2}$ cwt. of coal per ton of ingots made from cold charges quoted by Dr. Tigerschiöld must not be overlooked. As a matter of interest, it should be observed that 4 cwt. of coal per ton of ingots produced in 30-ton acid open-hearth furnaces, was common forty years ago when using South Wales "through" coal which contained an average of 8% of ash and which was gasified in small, brick-built, block gas-producers with dry bottoms. This latter fact imparts added importance to the production of dry-quality gas by whatever means it may be obtained and delivered to the consuming unit. It is not always possible to work at a saturated temperature of 58° C., as mentioned by Hulse and Sarjant, nor is it even desirable with certain classes of fuel. The introduction of a preheated blast might, however, favour the production of a dryer gas. There is also much room for consideration of a centralized gas-producing plant with a proper service for distribution to the various units in all self-contained plants. A cleaner and dryer gas should result from any such common service, although it must not be overlooked that the advantages associated with initial gas-producing temperatures will of necessity be lost.

With fuel containing up to 40% of ash for use at boiler plants, as is mentioned by Turner and Gray, there remains some hope of better utilization of the low-grade fine coal in this area but, here again, it would seem to be a matter of plant extension to meet requirements.

In dealing with the general emphasis attached to air preheating and the use of metallic recuperators for temperatures ranging up to 1000° C., as is mentioned by the several authors, there would appear to be good reason for giving careful attention to the desirable economy thus outlined and to where proved results have been attained. As oxygen gas becomes cheaper in conformity with its increased usage in industry, there is much to be hoped for in ultimately displacing the part use of air in several directions associated with fuel efficiencies.

These remarks constitute an expression of practical experience accumulated in the consumption of fuels as used in Yorkshire, Lancashire, Scotland, and North Wales, in addition to those specifically mentioned. It is, perhaps, hardly necessary to add that the fuels from South Wales present far greater difficulties than those associated with the other areas named, but they should not be regarded as insurmountable.

Mr. D. Kilby (Scunthorpe, Lincs.) wrote: There are two points in the paper by Turner and Gray which are of particular interest to the writer:

(1) In Fig. 1, the power consumption in therms per ton for the Appleby melting shop and the Templeborough melting shop is 4·2 and 1·0, respectively. One would expect the power consumption at the Appleby shop to be higher owing to double handling of, say, 80% of the charge, *i.e.*, pouring the metal into the mixer and then transferring it to the open-hearth furnace, as against direct charging from wagon to furnace at the Templeborough shop; or is it a question of using heavier cranes for comparatively light work? Could the authors clarify this point?

(2) Under "General Considerations" the authors refer to the virtual loss of a portion of the original heat content of the metal on its passage through the mixer. Generally speaking, it has been the writer's experience with active and semi-active mixers for the metal to be hotter when leaving the mixer than when charged. Was this not the experience at Appleby? If not, could the authors give temperatures of the metal entering and leaving the mixer?

The writer would like to congratulate Messrs. Turner and Gray on the clear and concise way in which they have dealt with so many aspects of fuel utilization in so short a paper.

AUTHORS' REPLIES.

Dr. Tigerschiöld wrote in reply: First of all I want to express my thanks for the kind reception of my paper and for the lively discussion which followed it. I am only too pleased, if any of our experiences in Sweden can be of use to the British iron and steel industry.

As to the questions of Mr. G. Doxey, I want to complete my remarks made during the discussion:

The life of the elements in the metal recuperators is naturally dependent upon the quality of steel used in these elements and upon the temperature of the blast. In the Swedish charcoal blast-furnaces, where these recuperators nowadays are predominating, the temperature of the blast runs at about 600° C. and the life of the tubes, when made of a steel containing 24% of chromium,

seems practically infinite. In fact, there are recuperators of this kind still running that were installed more than 15 years ago, where no repairing has been necessary. At higher temperatures a more expensive steel has to be used. It has been found that it is not so much the heat-resisting as the creep-resisting properties that must be improved. It is worth mentioning that the very good steels with 20–25% of nickel and 20–25% of chromium will stand blast temperatures of 800° C., but they will corrode very quickly, if the blast-furnace gas contains sulphur. Within a short time, tests will be made with compound tubes, where the inner layer is made of a creep-resisting steel and the outer layer consists of a heat-resisting plain chromium steel. It is expected that such tubes will make it possible to attain much higher blast temperatures.

I mentioned in my paper that tests will be made with an INKA preheater for steam up to 1000° C. The tubes for this preheater are made of a very expensive heat-resisting steel. The preheater in question will be started during this autumn, and the results will be of great importance for the development in this field.

Regarding the control of the temperature, this is done automatically from a thermocouple in the hot-blast main which gives impulses to a valve in the gas pipe to the recuperator.

Mr. Thring asks why the INKA preheater is not built with the convection preheater behind it instead of separating the radiant unit from the convection unit. This question is quite understandable, and such a construction could, naturally, be easily made. The reason is that the INKA company meant this preheater to be a complement to existing convection preheaters and not a competitor to this construction.

To the three questions of Mr. Kennedy I want to give the following reply:

The calorific value of the blast-furnace gas from the furnace working with a coke consumption of 13 cwt. amounts to about 80 B.Th.U./cu. ft.

It is true that the thermal efficiency of the recuperative hot-blast heater is decidedly lower than with normal stoves. The reason why the former construction has had such an extensive use in Sweden is that in the charcoal blast-furnaces they formerly used cast-iron tube stoves fired with uncleaned gas. Very often there was no place for Cowper stoves and gas-cleaning equipment. At lower blast temperatures the price of a metallic recuperator is much lower than that of Cowper stoves of corresponding capacity, and, besides, no gas-cleaning equipment had to be built.

The reason why blast-furnace gas very often is used in steam boilers instead of for metallurgical heating-furnaces is in the first place that the low heat value of the blast-furnace gas necessitates a preheating of the gas to obtain a high enough temperature in the furnace. The cost for installing blast-furnace-gas for heating will therefore be lower in a boiler than in most metallurgical furnaces.

Regarding Mr. Pearson's question I will mention that the analysis of the producer gas made from straw is as follows:

Carbon dioxide	8·0%
Carbon monoxide	25·1%
Hydrogen	7·9%
Methane	2·6%
Nitrogen	56·1%
Total	99·7%

A small amount of tar and quite appreciable amounts of soot follow the gas and, as I mentioned in my paper, it has been possible to fire open-hearth furnaces with gas made exclusively from straw.

Dr. Dunningham writes that he thinks that the recent developments of metallic recuperators open up possibilities to recover at least part of the sensible heat in producer gas and to bring this heat back to the producer. We have discussed this method very much in Sweden, and at the moment are making tests on a gas producer with hot blast together with varied portions of steam or waste gases under the grates. The results are not yet definite, but it seems to be possible to increase the heat value of the producer gas quite appreciably in this way. It will, however, be difficult to put in a recuperator in the gas main after the producer. The difficulties with soot and tar coverings will probably make this idea almost impossible to carry out.

Mr. Hulse, Dr. Sarjant, Mr. Turner, and Mr. Gray wrote in joint reply: The authors of the papers dealing with practice in the British iron and steel industry contribute the following joint reply to certain points in the discussion which appear to be of such a general nature as to merit this action.

It should not be necessary to correct an impression created by Mr. Mason's remark, certainly not intended but possibly apparent to the less well informed, that the institution of committees in the industry to study fuel is a new thing. Such an institution goes back many years. It must be apparent from the papers presented that intensive study of fuel problems in iron and steel works is a well-established practice. A feature of the present problem is the question of the dimensions of the effort, rather than of its existence. It is a significant fact that the early activities of the Technical Department of the British Iron and Steel Federation were directed mainly to matters of fuel utilization. It is possibly true to say that the outstanding success of the Ministry of Fuel and Power was due to the fact that it was able to

mobilize the existing technical forces in industry, which had been created during the intervening period between the two wars.

With regard to Mr. Mason's emphasis of the necessity of applying existing knowledge, this point has been repeatedly stressed in the co-operative publications of the iron and steel industry.

The authors are grateful to Mr. Mason for having reinforced the implications of their arguments in such a forceful manner.

We have appreciated very much the contribution of Mr. Doxey and have noted with full agreement his remarks concerning further investigation and the advantage of closer co-operation between the iron and steel industry and the instrument makers. We would wish to support his plea for research into the aerodynamic aspects of burner design, and for the provision of a reasonably priced oxygen recorder. Mr. Whitfield expressed the opinion that in metallurgical practice the oxygen indicator and/or recorder serves a better purpose than the CO_2 indicator. We entirely agree with this view.

In reply to Mr. Armstrong's contention that coal is our finest fuel we do not concur with his view. Essentially, coal is a valuable raw material for the production of numerous chemical products, which ideally should be separated, and only the residuals used as fuel. This view has frequently been urged in the past. We are somewhat in doubt as to what Mr. Armstrong means by associating speed of combustion with air/gas ratio but we agree thoroughly with his remarks about the neglect of air control valves. We would emphasize, too, the neglect of the damper in this connection. In the Furnaceman's Manual of the Ministry of Fuel and Power, intended for the use of furnace operators, a special effort is made to drive home the importance of the combined use of the fuel, the air control valves, and the damper. The tendency in modern progress is to overcome these disabilities by the introduction of automatic control. We are unable to understand why Mr. Armstrong puts the recovery made by his ordinary waste-heat boiler as low as 13%. We should have expected him to have put this figure very much higher.

Referring to Mr. Thring's contribution, there is a vital need at the moment for a "quantum jump," but this depends not on the progress of research so much as on the skill and enthusiasm with which the results of research are applied practically.

We heartily agree with Mr. G. A. Young's suggestion that coal should be sold on a basis of the calorific value or ash content. Further, with regard to the price basis, it must be apparent to everyone that the price should vary with the true industrial value of the coal.

With reference to Dr. Durrer's remarks on the concentration of the oxygen in the blast used by the Russians for smelting iron ores, we interpret his figure of 70% as meaning that the oxygen concentration had been taken to 35·7%, that is to say, that his figure refers to an addition of 70% of the normal oxygen content of the atmosphere.

Dr. Grumell writes with the high authority of the Chairman of the Fuel Efficiency Committee of the Ministry of Fuel and Power and we are very grateful to him for his remarks. We strongly agree with his advocacy of the provision of frequent opportunities for experts to get round a table and thrash out not only practical problems of operation and design, but also the question of research. We think, too, that there should be brought into such conferences the technical elements of industry which are concerned with the more indirect aspects of the application of fuel.

With regard to Mr. Stirling's opening paragraph, we would certainly go further and state that the shift of emphasis he advocates should go even beyond the condition of the combustion gases and deal with the design and operation of the plant as well. We are not clear as to what he means in his remarks about Sankey diagrams, and wish that he had elaborated his suggestions.

We thank Mr. Edgar Williams for his support of our suggestions in general and for his confirmation of Mr. Armstrong's opinion about detailed study of the papers. We note with interest that he joins issue with Mr. Mason on the question of gas-producer efficiency. It could certainly be concluded from his remarks that substantial contribution towards the improvement of gas-producer practice would be effected by the supply of better-graded fuels. Following up the point raised by Mr. Williams about centralized gas-producing plant, it is possible to take as an ideal the provision of such plants for non-integrated types of works. The use of a distributed clean gaseous fuel enables furnaces to be designed which have a higher standard of efficiency than that possible with almost any type of raw fuel. The suggestion entails, of course, the prosecution of considerable fundamental research into the raising of the cold-gas efficiency of the generating plant. Some means must be found of utilizing sensible heat in the gases and, possibly, of using it in preheating the blast. Dr. Dunningham supported this view. The provision of cheaper oxygen would contribute towards the attainment of this ideal.

We are glad to have had the opportunity of taking part in such a stimulating meeting, and we thank all contributors for their interesting remarks.

The following addenda apply to points which have been raised in regard to particular items in the separate papers.

Mr. Hulse and Dr. Sarjant also wrote in reply: Mr. Mason has raised a controversial point on gas-producer efficiency. In this connection it is important to distinguish between hot-gas efficiency at the furnace and hot-gas efficiency at the producer. Whilst he expressly referred to producer efficiency, we think he must have had in mind the efficiency at the furnace which certainly requires to be raised.

In reply to Mr. Doxey it is intended to follow up the study of variable flow of heat in furnace structures, since it is realized that hitherto it has only been possible to approach this type of problem in an approximate manner owing to the lack of any suitable technique for the purpose.

It is gratifying to have such a powerful advocate as Mr. H. C. Armstrong on one's side. We must confess that when we first heard Mr. Armstrong's opening commendation of our paper, doubts immediately arose in our minds whether there might be something seriously wrong with it, for we had in mind the ancient passages of arms, which incidentally had done much to stimulate thought, and the well-known didactic skill of the speaker in picking one up gently to drop one finally all the more heavily. We breathed a sigh of relief when we realized that the speaker was this time in earnest. We agree fully with his trenchant remarks on the need for a healthy dissatisfaction with present conditions, and it is to be hoped that they will be as widely read as the papers.

On the question of rates of heating raised by Mr. Armstrong, it is essential to draw a distinction between conditions which involve a time factor determined solely by metallurgical considerations and those in which the conduction of heat alone is involved. Recent developments of high-intensity burners and the possibilities foreshadowed by machine methods of computation have shown that steel can be rapidly heated. More uniformly heated furnaces are required for improvement of efficiency in this respect. Return of sensible heat of the waste gases is a separate requirement.

In reply to Mr. Thring, a non-water-cooled heat-flow meter is required for the many situations and conditions in plant survey work in which the use of water on an extensive scale is entirely ruled out. We agree that in the case of an open-hearth furnace in a large melting shop the use of water presents no real difficulties.

In regard to the relative merits of coal and oil, raised by Mr. Kennedy, these questions are mainly of an economic character. Our point was rather to stress the fact that the technical problems involved are comparatively simple.

We are indebted to Mr. Pearson for his discussion of the point we raised in regard to the existence of an optimum figure for the calorific value corresponding to a specific blast saturation temperature. Whilst this is also apparent from Gibson and Gwyther's investigations on a small suction gas producer of 30 h.p., gasifying coke at the rate of 30 lb./hr., these investigators did not discuss the significance of the observation. The same type of marked optimum is not apparent in the investigations of either Bone and Wheeler * or Clements,† which dealt with the use of bituminous coal. It is appreciated that the optimum observed could be due to a change in the balance between the exothermic and endothermic reactions, but these depend upon the temperature of the reaction zones, the equilibrium constants of the various reactions concerned, and their reaction velocities. The resultant effect depends to some degree on the condition of the fuel bed which cannot be excluded from consideration. Our data related to a type of producer in regard to which the relationship found had not previously been reported as far as we are aware.

We cannot agree that Mr. Pearson's explanation appertains to the conditions existing in the producer in question. His Fig. A is certainly interesting, but its implications do not accord with the results of the classical investigations on air–steam-blown gas producers. We should have thought that a smooth curve drawn through the experimental points in his curve, for example, for carbon monoxide, would have been more justifiable, the divergence from the mean curve being regarded as due to experimental error.

On the question of the measure of the H_2O reaching the reaction zone, our experience has been that moisture in the blast—particularly the finely divided particles of water arising from the wetness of the steam—is lost in the ash bed by condensation and/or filtration rather than gained by evaporation. This is apparent from measurements of steam actually metered to bituminous-coal producers and that found in the gas as either decomposed or undecomposed water vapour. In the present case we should recall that the producer is of the dry-bottom type, and water of condensation is known to drip constantly from the ash hopper.

Mr. Whitfield has raised a subject of considerable magnitude in discussing the term "neutral atmosphere." We do not think such exists in the normal atmosphere of industrial furnaces. We may recall a case, discussed ‡ some years ago, when a furnace charge with a final atmosphere of composition of over 10% of carbon monoxide, 14% of carbon dioxide, and no oxygen, showed evidence of decarburization. We note with interest Mr. Whitfield's distinction between the

* W. A. Bone and R. V. Wheeler, *Journal of The Iron and Steel Institute*, 1907, No. I., p. 126.

† F. Clements, *ibid.*, 1923, No. I., p. 97.

‡ R. J. Sarjant, *Journal of the Society of Chemical Industry*, 1930, vol. 48, p. 465T.

oxidation effects of underfeed and overfeed types of mechanical stokers. Surely, equivalent results should be obtainable on either type, if suitably controlled.

We should hate to have to operate pulverized-fuel-fired metallurgical furnaces on Mr. Whitfield's coal with 25% of ash.

Obviously enthusiasm and drive have produced the results which Mr. Whitfield mentions in his reference to education. Unfortunately, such conditions do not apply equally to all industrial establishments. An important educational principle is also involved in these other cases—the provision of the necessary skilled instruction which needs to be of a very high order. A far better solution as a general principle is in our opinion the institution of a properly constituted national scheme of education which embraces all types of conditions.

Mr. Turner and Mr. Gray also wrote in reply: The figures quoted by Mr. Mason as the average for gas-producer efficiency throughout the country appear unduly low. Mr. Kennedy's remarks confirm this opinion. It may interest Mr. Mason to know that the gas producers operating in the plants of The United Steel Companies, Ltd., work with a hot-gas efficiency close to the optimum figure mentioned.

With regard to Mr. Doxey's remarks concerning tar, we feel that crude tar is too valuable a source of chemical products to be used as a fuel, but appreciate that what he says could as well be applied to residual products of tar distillation.

Mr. Armstrong brings an accusation of complacency which we consider wholly unjustified. While agreeing that finality in fuel saving can never be reached, we are strong believers in the saying "physician heal thyself" and accordingly have not feared to show what we have so far accomplished.

The interpretation put by Mr. Armstrong on part of the statement that we made in connection with changing over of furnaces from coal firing to gas firing is somewhat tendentious. We do not doubt that very efficient coal-fired furnaces can be met.

Mr. Kennedy wishes to have our view as to the function of the fuel engineer. We do not think we can say much more than he says himself, except to emphasize that we agree with him that the responsibility of the fuel engineer does not finish with fixing the limits of the amount of fuel which should be used on a furnace or the control of the combustion of this fuel.

Concerning the capacity of the gas-holders used in connection with the Orgreave plant, it is our opinion that as each case has to be judged on its own merits, no advantage would be served by discussing the reasons which led to the decision in this case.

We find Mr. Bagley's contribution very interesting, but its value would have been enhanced had he given either the cost of the oxygen or the power required for its production.

In answer to Mr. Kilby's remarks we would say that:

(1) The power consumption at the Appleby melting shop includes for items which are either non-existent at Templeborough, such as furnace-tilting gears, or for plant of different capacity, *e.g.*, cooling pumps; thus the comparison of a special item such as crane power is rather vitiated.

(2) It is true that metal increases its temperature in passing through the mixer, but the heat gained is only a fraction of that contained in the fuel consumed by the mixer and, even after making allowances for any metallurgical gain, there is still an overall heat loss which can be expressed as a virtual loss of a portion of the original heat content of the liquid iron.

SOME ASPECTS OF THE OVERHEATING OF STEEL DROP-FORGINGS.*

By H. J. MERCHANT (Commercial Steels and Forge Co., Sydney, Australia).

(Figs. 1 to 42 = Plates VII. to XII.)

Synopsis.

The effects of overheating on the serviceability of steel drop-forgings, particularly in relation to their use in aero-engine construction, are discussed. The principal causes of, and factors influencing, overheating are described, and an attempt is made to differentiate between overheated steel, severely overheated steel, and burnt steel. The greater part of the paper is devoted to a description of the methods used to detect overheating in alloy steel, namely, examination of the surface and of the fracture, metallographic examination, and mechanical testing. Work carried out with a view to studying obscure aspects of the subject, together with an attempt to establish fracture-test standards, is described. An account is given of methods of preventing overheating and of reclaiming overheated steel. Finally, there are some notes on the occurrence of overheating in American steels, and some suggestions are given regarding directions which might be taken by future research on this subject.

Introduction.

An interesting problem concerning the condition of forgings and drop-forgings which had been overheated in their manufacture, arose during the war. Until recently, alloy steels have to some extent been regarded as possessing properties which render them more immune from the effects of overheating than carbon steels. However, the technique employed in forging alloy steels has an important bearing on the ultimate serviceability of the part; steel which has been overheated may be detrimentally affected to varying degrees which are difficult to detect by normal inspection procedures. Perhaps the most exacting use to which alloy-steel drop-forgings are put is in the construction of aero-engines, and it was chiefly in this connection that complaints arose concerning defects which were attributed to the overheated condition of the steel. Such parts as connecting rods, valve rockers, gears, &c., have failed prematurely by fatigue as a result of the steel having been overheated, fatigue cracks being more easily propagated from the boundaries of large crystal grains at or adjacent to zones of high local stress in loaded components. During the war, aero-engine power has been increased, but the strength or weight of the components has in most cases remained the same. This has revealed, and necessitated the detection of, an overheated condition in drop-forgings which may or may not have occurred in varying degrees previously. Fortunately, the methods, often drastic and costly, adopted by aero-engine manufacturers to detect overheating have prevented such steel from going into service. Again, it is possible that other alloy-steel forgings have suffered from overheating which has perhaps not been revealed because they were not subjected to such high loads and alternating stresses as occur in modern aero-engines. The overheating of steel drop-forgings has not been confined to British practice alone, but has been experienced in the United States and elsewhere. Overheated steel may be present in components which have fulfilled every routine test required by the present aircraft specifications. It must be understood that the term "overheated" does not apply to a steel which has suffered "burning" or incipient fusion visible microscopically; such material has distinctive features which are easily detected by normal inspection methods. The purpose of this paper is to discuss various aspects of the causes of, and factors influencing, overheating, the nature and detection of overheating, and the methods adopted to prevent and reclaim overheated forgings.

Causes of Overheating.

In general, overheating of steel forgings is caused by either: (1) Heating the bar or semi-finished forging to too high a temperature, or (2) keeping the steel for prolonged periods at what are considered normal forging temperatures. These are the main causes, but other factors influencing overheating are: (3) Amount of hot work, (4) furnace atmosphere, and (5) composition

* Received December 7, 1945.

of the steel. These factors will be discussed more fully.

(1) *Temperature of Heating.*

This is the most frequent source of overheating, the maximum desirable temperature being exceeded in practice owing to a number of causes. Forge furnaces operating at 1200–1400° C. do not lend themselves easily to pyrometric control, and only in the last few years have instruments been developed which can withstand forge conditions and at the same time give accurate and reliable automatic temperature control. In many British plants the nearest solution to the problem has lain in the use of manually operated optical pyrometers. With such a method, overheating must occur at times, because there is no absolute control over the furnace temperature. In addition, the temperature of a piece of steel as measured on withdrawal from the furnace may not be a reliable indication that the steel has not been overheated, since it may have attained a higher temperature earlier in the heating period. It is possible, too, that in the reheating of semi-finished forgings, any part of small section or any projecting bosses or flanges may have been exposed to the furnace atmosphere and have exceeded the maximum safe temperature, although the main section of the forging has been heated correctly. The employment of furnace temperatures exceeding the prescribed maximum is usually due to a desire on the part of the operator to obtain increased production by heating the steel to temperature in the shortest possible time, or to the desire of forgemen to make a part in one heat instead of two. Rapid heating may result in the outside of the steel being overheated before the centre has reached forging temperature; the same may occur when several pieces of steel are heated together.

In some furnaces the design is such that the steel is subjected to flame impingement. This occurs when the heating flame is injected directly into a furnace and the steel is not shielded by a baffle wall. Flame impingement causes local overheating, which is not readily detected by pyrometric means and which must be regarded as one of the drop-forger's chief problems. Many forge furnaces are fired by pulverized fuel, and if this is not properly controlled, there is a danger of the fuel falling on to the steel and perhaps causing local overheating.

In other furnaces the design is such that there is uneven distribution of temperature from one side to the other, and the steel may be transferred to the hot side if a high production rate is desired. Under such conditions it is important that the temperature of the hottest zone be kept within a reasonable margin of the practicable minimum forging temperature.

(2) *Time of Heating.*

An overheated condition may also arise from holding the steel for far too long a time at what are considered maximum or even normal forging temperatures. This is often due to lack of control by the operator, particularly in batch-type furnaces, and can be overcome only by experience and by educating the operator, or by employing continuous furnaces which eliminate the human element altogether. In the case of semi-finished forgings, any thin sections are necessarily held at temperature longer than thicker sections, and this may lead to some localized overheating.

At the beginning of the war a bottleneck existed in the manufacture of steel drop-forgings which eventually resulted in the setting up of new plants which were staffed with more or less inexperienced labour. The demand for increased production left little time for training and instructing the operators properly, in some cases with dire results. With untrained operators, failure to withdraw steel from the furnace during spells of hammer trouble or maintenance was a common cause of overheating. The necessity for orderly charging and discharging of the furnaces was not always apparent to the untrained, and the author has seen cases where steel was allowed to reach such a temperature that it had to be cooled, generally on the dies, before it was safe to forge; otherwise disintegration would have taken place. Fortunately, such a state of affairs was checked soon after its evils became apparent, and only men who were interested in their furnaces were allowed to make the important jobs.

(3) *Effect of Hot Work.*

The effect of work on steel in the austenitic state is to refine the coarse structure formed as a result of heating, and, up to certain limits, the more work it receives, the more refined will be the resultant structure. There is a difference of opinion at the moment as to whether hot work refines an overheated structure or not. From a practical point of view, the importance of sufficient hot work cannot be over-estimated. It is more satisfactory to make a forging in one heat, if possible, even if this involves the use of multiple die impressions or larger hammers or two hammers teamed together, than to have to reheat the semi-finished forging and finish it in an operation which does not give adequate grain-refinement. Forgings which, for some reason or other, have been reheated and "retapped" to size (as, for example, after blending-out defects) have in many cases been overheated.

One further aspect of the effect of hot work on forgings is that the energy dissipated in deformation results in an increase in temperature, especially in the early stages of maximum dispersion, as, for example, in drawing-down a thin shank.

The safe maximum temperature may well be exceeded, and some authorities have regarded this as a possible cause of overheating; but it must be remembered that such temperatures exist only momentarily, because the steel responds to the cooling effect of the dies as it approaches its final shape.

(4) *Furnace Atmosphere.*

The effects of furnace atmosphere on overheating are rather obscure, but existing evidence indicates that a strongly oxidizing and turbulent atmosphere results in overheating at lower temperatures than do less turbulent and less oxidizing furnace conditions. Some research on this subject with nickel–chromium–molybdenum steels is now being conducted by the Alloy Steels Research Committee [1] and results are awaited with interest.

(5) *Composition of the Steel.*

Steels of different compositions vary considerably in susceptibility to overheating. Mild steel, for instance, appears to be least susceptible, whereas higher-carbon and low-alloy steels are more susceptible, and high-alloy steels—particularly the nickel–chromium–molybdenum types—are easily overheated. Although, in the past, maximum forging temperatures have been prescribed from the solidus line of the iron–carbon diagram with extrapolation for the alloying elements, there appears to be no direct relationship between the composition of the steel and the temperature required to produce overheating. Maximum forging temperatures must therefore be largely a matter of practical experience until more is known on the subject. Susceptibility to overheating also appears to be affected to some extent by the steelmaking process, basic electric-furnace steels being more susceptible than basic open-hearth steels of the same composition.

The Nature of Overheating.

A study of the nature of overheating in steel must necessarily entail a knowledge of the states closely related to overheating, namely, burnt steel and steel free from overheating and burning. The burnt state in steel has been studied by several eminent metallurgists, but their work—with one important exception [2]—has been confined to plain carbon steels, where the symptoms of overheating and burning are a great deal clearer than in the case of alloy steels. The present work is largely confined to alloy steels, and, from some experience gained in the examination of overheated drop-forgings, it appears that the steel may be in a number of conditions, depending on its thermal and mechanical treatment in the forging process. For the purpose of this section of the paper, four conditions are selected for discussion, namely, (1) burnt steel, (2) severely overheated steel, (3) overheated steel, and (4) satisfactory steel, *i.e.*, steel free from overheating.

(1) *Burnt Steel.*

Burnt steel is easily recognized. The temperature of the steel has been so high that fusion of the low-melting-point constituents and intergranular oxidation have occurred. It is also possible that liberation of gases may occur during burning and that carbon monoxide may be formed by the reaction between oxygen absorbed from the atmosphere and the carbon in the steel. Considerable grain growth occurs, and the mechanical properties of the steel suffer considerably, particularly the ductility and impact resistance. The fracture of a burnt steel is coarsely granular, the mat facets of the crystals having slightly curved faces; sometimes oxide coloration of the facets is observed. A burnt forging is readily detected at the surface by mild pickling; when the scale is removed, intercrystalline cracks, typical of burning, are revealed. If burning is severe, the steel loses its plasticity and may disintegrate under deformation. Fig. 1 shows the appearance of a billet of burnt steel after one blow under the hammer. If the burning is not too severe and the method of working not too drastic, the steel may pass into service without the defect being detected, and subsequently fail by lack of intercrystalline cohesion. Fig. 2 shows typical burning cracks revealed by magnetic crack detection on a section of a machined, upset, ring forging. Microexamination of burnt steel reveals oxide films or coalesced globules of the low-melting-point constituents or voids at the large crystal boundaries. Figs. 3 and 4 show typical microstructures of a burnt plain carbon steel at low and high magnifications, respectively.

The subject of burnt alloy steels, as distinct from the burning of steels generally, was studied by Austin.[2] In Part 1 of his paper some account of the work of preceding investigators is given, and here it may be useful to indicate briefly the theory of burning of steel up to the time of Austin's work. Earlier metallurgical writings, such as those of Stansfield,[3] Howe,[4] and Sauveur,[5] showed that the original conception of burning was that of a partial fusion of the metal itself—probably as a result of its attaining temperatures above the solidus line—and sometimes accompanied by intergranular oxidation. Stead [6] introduced a slight modification to the theory by suggesting that phosphorus-rich envelopes would melt at a point just short of fusion of the steel. Tammann [7] and Houdremont [8] extended this view to include the fusion of intergranular phases, such as oxides or silicates or even carbide or sulphide enrichments, occurring as envelopes around

the crystal grains. It was at this stage that the work of Austin was published. This work had arisen from the examination of several alloy-steel air-containers which had failed unexpectedly at very low stresses and which fractured with a course, mat, granular fracture. A large number of mechanical tests carried out on several different samples exhibiting the same phenomenon gave very poor fatigue values for the material. Micro-examination showed that etching with strong acids was generally necessary to reveal the defect, and an acid etchant consisting of a solution of 10% sulphuric acid and 10% nitric acid was particularly recommended; this outlined in the micro-section polygonal grains the distribution and size of which coincided with the granular fractures and which were considered to be evidence of the same phenomenon. Many of the facets had slightly curved surfaces, and since it was not possible to remove the defect by normal heat-treatment, it was considered that the cell wall outlined in the faceted fracture was of a fixed insoluble nature at normal heat-treatment temperatures. The whole phenomenon was ascribed to severe overheating or burning, and was explained by the fusion of the inclusions or segregates which flowed by capillarity round the grain boundaries then existing.

The effect of the phenomenon on the mechanical properties of the steel was not confined to the fatigue strength alone. The presence of burning in the steel arrests the normal load/elongation curve obtained in the tensile test to a degree varying from failures actually within the elastic range in very bad cases, to those within the necking range of the test in the case of steels only slightly affected. A more important observation was that the " tearing strength," or mean stress at fracture, was reduced as a result of the intergranular nature of the defect. The ductility, as measured by the elongation and particularly by the reduction of area, was also reduced. Finally, the impact resistance was considerably reduced, often below the specification value. The fatigue tests were most interesting, since such tests are not usually specified on account of their lengthy nature, the fatigue strength being usually assessed at approximately 40–50% of the maximum load for heat-treated nickel–chromium–molybdenum steel. Austin's results on burnt steel indicated values as low as 28% of the maximum load (*i.e.*, a reduction of 44% in fatigue strength) but, in general, slightly low and irregular fatigue values were obtained, which were ascribed to the uncertain nature of the defect. For some time it has been accepted that the fatigue limit is mainly a function of the resistance to deformation and does not depend on the plasticity or ductility or notched-bar impact strength of the steel. It would therefore appear that unless burning is severe enough to affect the maximum load, it should not appreciably reduce the fatigue limit. There is, however, another consideration, and that is that the grain boundaries or films of fused inclusions are likely to exert a considerable notch effect, which would be detrimental to the fatigue life of high-tensile steel. It is for this reason that overheated steel should be viewed with suspicion and its thermal history fully investigated.

Burning is an intergranular phenomenon. The cohesion between the crystals decreases rapidly as the metal is heated to temperatures approaching the solidus, and the force of surface tension which tends to make each crystal assume an almost spherical shape may in some cases be sufficient to destroy the cohesion between them. This approach to a spherical shape is reflected in the slightly curved surfaces of the crystal facets in the fracture of burnt steel. Any internal stress in the steel set up by temperature gradients during the heating may also cause intercrystalline rupture when a sufficiently high temperature is reached. From a practical point of view the temperature at which steel burns cannot be ascertained from the iron–carbon diagram. The presence of such elements as manganese, silicon, and phosphorus, even if uniformly distributed, will lower the temperature of burning. In steel, these elements and the carbon are not uniformly distributed, but are segregated at the crystal boundaries, and the melting point of such regions may be lower than that of the steel generally. Incipient fusion may thus well occur where the impurities are concentrated, but this theory does not explain all the aspects of burning. For instance, voids may form in the interior which cannot be attributed to fused metal, since the latter obviously could not flow away. It is likely that the effects of surface tension, of internal stress, and probably of liberated gases too, on the melting point of the less pure intercrystalline metal combine at high temperatures to cause burning.

When steel is exposed to an oxidizing atmosphere, oxygen may penetrate the metal and form crystal-boundary films beginning at the surface and proceeding inwards; it is also possible that oxygen may diffuse through the sound metal and form oxide in any voids already present. The furnace atmosphere is therefore a factor in burning, although not an essential one, since Jominy [9] has shown that steel may be burnt by heating in a vacuum, and that while steel burns at temperatures near the solidus when heated in a neutral or reducing atmosphere it burns at 100° C. lower when heated in an oxidizing atmosphere. Thus it appears that the presence of oxygen lowers the burning temperature, either because of the formation of intercrystalline oxide films or of the production internally of carbon monoxide by the reaction between diffused oxygen and the carbon in the steel.

(2) *Severely Overheated Steel.*

Steel which has been overheated but not burnt is more difficult to detect; often there is no external indication of overheating. However, when an overheated steel is pickled carefully, the surface may take on a "crocodile-skin" or "crozzled" appearance, the severity of which can be an indication of overheating, although its absence would not indicate that the steel had not been overheated. The most reliable evidence of the severely overheated condition is found in the fracture test. Fractures of such steel are always granular, the size of the crystal facets depending on the degree of overheating. A distinguishing feature of this stage is the golden-brown coloration of the crystal facets, which has been attributed to the presence of very fine intergranular oxide films, not normally detected by orthodox micro-examination. Such a steel has low impact and ductility values, though often not below specification requirements; the fatigue properties may be reduced to an unknown degree, which may affect the serviceability of the part. There is no evidence at the moment to show that steel overheated to this degree can be refined by any form of heat-treatment. As in the case of burnt steel, it is likely that a definite minimum temperature is required to produce the condition, and that other factors affecting overheating, such as the time at temperature, the amount of hot work, &c., have less effect.

(3) *Overheated Steel.*

This stage resembles the preceding one, except that the amount of overheating is not so great. In this case, the length of time at which the steel was held at temperature has probably had more effect than the temperature itself. Another possible factor contributing to this condition is the lack of sufficient work to break down the large crystal structure resulting from the heating. The fracture of overheated steel is granular, the size of the crystal facets depending on the degree of heating; often, only part of the fracture is granular, this being set in a fibrous matrix. In this condition there is no coloration of the facets on a newly fractured surface, and a further distinguishing feature of the less severely overheated condition is that it responds fairly satisfactorily to refinement by suitable heat-treatment. The mechanical properties of steel in this condition may be only slightly impaired by overheating.

(4) *Satisfactory Steel.*

In forgings, a satisfactory condition is one which responds to heat-treatment without difficulty, gives good mechanical properties, and has a fine silky-to-fibrous fracture characteristic of a ductile steel. The surface appearance is normal, and the microstructure shows no evidence of the steel having been overheated. The steel has been carefully heated for the right time at the correct temperature, and then has been given sufficient work to refine the comparatively large crystal size produced by heating to the forging temperature; the work should have ceased just above the critical range of the steel so that the finest possible grain-size is obtained.

The Detection of Overheating.

The methods which have been used to detect and confirm the presence of overheating in drop-forgings may be listed as follows: (1) Surface examination, (2) fracture examination, (3) metallographic examination, and (4) mechanical tests. In many instances a combination of two or more of these methods has been used, and therefore they need consideration in detail.

(1) *Surface Examination.*

High-quality steel forgings for aircraft purposes are descaled for inspection after forging and heat-treatment and before machining. Visual inspection may reveal burning in the form of deeply embedded scale and intercrystalline cracks. Small intercrystalline cracks not visible to the naked eye can be revealed by magnetic inspection, but often this is not employed on forgings, especially as the final machined part lends itself more readily to this method of inspection. It is fortunate that in some steels overheating is accompanied by a characteristic surface condition which is revealed by pickling in acid. This has been referred to earlier as "crocodile skin" or "crozzling," but it is also known by the names of "chicken-wire network" and "morocco-leather skin," and, as these names suggest, consists of an intercrystalline network of fine cracks or lines resembling morocco leather or crocodile skin. It may also be described as a deeply etched cellular structure. The pickling acid penetrates to a depth of 0·002–0·003 in. into the superficial grain boundaries which have formed during heating for forging. The existence of this cellular structure on the surface of a forging has been taken by some authorities as indicative of overheating, but in the early part of the present investigation difficulty was experienced in correlating this "superficial grain-size" as revealed by pickling the surface of a forging, with the internal grain-size as revealed by the fracture test or metallographic examination. Experimental work on the effect of hot work on an overheated steel showed, however, that the interior of the steel could be refined by forging, leaving the surface grain-size more or less the same as that produced by the overheating, but perhaps distorted if the flow of metal had been considerable. Crozzling can be regarded as an indication of the preferential affinity for heat of

the material at the austenitic grain boundaries at the maximum temperature attained by the steel.

The crozzling phenomenon has not been taken by all authorities as evidence of overheating, and some hold that it can result from certain furnace atmospheres. Nevertheless it is a useful guide, and forgings which exhibit it when pickled must be regarded with some suspicion. It is an undesirable surface condition in itself, especially if the forging is not machined all over, and at least one case came to the author's notice where premature fatigue failure in a very highly stressed but only very lightly machined part was attributed to it. Fig. 5 shows a fracture test-piece exhibiting acute roughness of the crozzled skin adjacent to the fracture. Fig. 6 shows a half-section of an upset gear-blank forging which had been macro-etched to show the grain flow and which revealed (among other defects) a penetration of the crozzling phenomenon into the body of the forging. This particular forging had been re-struck on account of a dimensional defect, and there had been no opportunity for any work to refine the overheated structure.

Different steels appear to respond differently to crozzling, and experiments were carried out on a number of well-known aircraft steels to investigate this. Samples of steels having a flat surface in the rolling direction were overheated for different periods of time in a forge furnace fired by pulverized fuel at temperatures of 1200°, 1300°, and 1400° C. After heating, the samples were cooled in air, pickled in boiling 50% hydrochloric acid for ½ hr., washed, scrubbed, again washed, and quickly dried. The crozzled skin of the samples was then examined and photographed under low-power magnification and oblique illumination. This examination revealed that high-alloy steels, particularly nickel–chromium steels, show more response to crozzling than low-alloy or plain carbon steels, and also that steels made by the basic electric-furnace process show a better-defined crozzling than those made by the basic open-hearth process. It appears that in low-alloy and plain carbon steels, and in steels made by the basic open-hearth process, there is a marked tendency for the longitudinal rolling fibre to persist. Figs. 7, 8, 9, and 10 show the surfaces of samples of the basic-electric nickel–chromium–molybdenum case-hardening steel, *S*82. Fig. 7 shows the surface of a control sample (from the rolled billet, *i.e.*, not heated) and Figs. 8, 9, and 10 show the crozzling after heating for ½ hr. at 1200°, 1300°, and 1400° C. respectively. These show uniform increase of crozzling or superficial grain-size with increase of temperature, and as the steel was not worked after overheating, the surfaces agree well with the fracture tests carried out on the same samples and referred to later. Figs. 11, 12, 13, and 14 show the surfaces of other aircraft steels after heating at 1300° C. for ½ hr. in the same furnace. Fig. 11 shows the surface of a basic open-hearth plain carbon steel, *S*6, revealing the fibre of the steel, with signs of mild crozzling under the surface. Fig. 12 shows a similar phenomenon in the comparatively low-alloy manganese–molybdenum steel, En 16, made by the basic open-hearth process. Fig. 13 illustrates the clear and well-defined crozzling which occurred with a cast of basic-electric 3½% nickel steel, *S*69, whilst Fig. 14 shows the more confused crozzling which occurred with a basic open-hearth cast of a 3% nickel–chromium–molybdenum steel, 4*S*11. Crozzling occurred to an equal degree in both case-hardening and deep-hardening alloy steels and was not confined to those containing nickel, for samples of En 18 (1% chromium steel containing no nickel) and En 40 (3% chromium–molybdenum nitriding steel containing less than 0·40% of nickel) were tested and showed definite evidence of crozzling. It was observed, on the other hand, that steels which did not contain some chromium showed a very poor reaction to crozzling.

Various pickling procedures have been employed for the detection of overheating in forgings or in the finished-machined parts made from them. One aircraft-engine manufacturer favoured the use of boiling 50% hydrochloric acid in which the forgings were pickled for periods of up to 30 min. After pickling, the forgings were washed, rinsed in an alkaline solution to remove traces of acid, rewashed, rinsed in nitric acid to remove carbon deposits, again washed, and quickly dried. The forgings were then examined without delay before rusting occurred; white fluorescent lighting and a magnification of 10 are helpful in viewing this work. As the pickling procedure was used only as a preselective test and guide to the presence of overheating, forgings were graded for further examination according to the severity of the crozzling, *e.g.*, none present, slight crozzling, large grains evident, and severe crozzling with evidence of oxide being dissolved from the grain boundaries. If the surfaces of the forgings have been distorted, as in coining operations, or even in heavy shot-blasting or light machining, pickling may not reveal the crozzling phenomenon. A disadvantage of this etching procedure is that it is not very practicable from a forge-shop production point of view because, firstly, there is difficulty in obtaining suitable large-scale pickling equipment and, secondly, many drop-forgers favour shot-blasting as the quickest and most efficient method of descaling.

Another etching procedure developed for use on important finished components was the use of an electrolytic etch in cold 50% sulphuric acid. Components were first given a 5-min. anodic etch followed by a 5-min. cathodic etch, which produced a selective attack on the grain boundaries

that was readily seen under low-power examination. Yet another method consisted of etching suspected forgings with a cold aqueous solution of 10% nitric acid and 10% sulphuric acid, followed by micro-examination at 100 magnifications. A polish approaching that necessary in metallographic examination is required, and the etching technique is similar to that described by Austin.[2] These last methods are somewhat tedious and lengthy and difficult to adopt on a satisfactory production basis. Up to the present, the use of etching methods has not led to the adoption of definite standards of evidence of overheating, but these methods have the advantage of being non-destructive. The crozzling indications are not always reliable, possibly because of variations in furnace atmospheres, or because work on the forging involves considerable displacement of surface metal. However, surface examination following pickling has been employed to a fair extent as a preliminary guide to the presence of overheating, which has afterwards been confirmed by fracture tests or further metallurgical examination.

(2) *Fracture Examination.*

A fibrous or ductile fracture is always expected of steels in the fully heat-treated condition, and if a granular or brittle type of fracture is obtained in such a condition there is obviously some structural explanation required for it. The fractures of overheated or burnt steel are distinctive from those of satisfactory steel in that they are granular instead of fibrous, with the mat facets of the crystals appearing more or less coarse according to the degree of overheating which the steel has received. This type of fracture is peculiar to steels which have been subjected to overheating and burning, and it has become usual to submit suspected parts to a fracture test. This test has obvious limitations in that it is destructive, and since overheating is a spasmodic trouble, testing on a percentage basis is not completely satisfactory. Nevertheless, the fracture test has been universally adopted, both in Britain and America, as a method of routine works inspection by drop-forgers and aircraft-engine manufacturers.

The fracture test comprises nicking, heat-treating, fracturing, and examination of the fracture. Nicking is necessary in order to facilitate fracture at a particular place. Experience has shown that it is essential for a forging to be nicked in as many places as possible consistent with ability to fracture the piece. Nicking may be carried out by a saw, milling cutter, or elastic wheel; the last named is preferable on account of its speed and versatility. A foundry-type cutting-off machine for removing risers has proved very adaptable for such work. It is, of course, often necessary to nick more than half way through the forging, especially on large components, and the area left for fracturing will depend on the fracturing force available. Many forgings made by the upset method, such as gear-blanks, rings, collars, and flanges, need be broken across only one diameter, especially if they are symmetrical. Forgings made "off the bar," however, need careful attention when carrying out the fracture test. For example, the "front end" of the bar may have been hotter than the remainder, and varying amounts of work may have been done on different sections of the forging. Many large and important aircraft forgings carry integral test-bars, and a fracture examination may be made on either impact or nicked-fracture test-pieces machined from the integral test-bar. When planning the manufacture of such forgings, the position of the integral test-bar needs careful consideration, as it should receive exactly the same thermal and mechanical treatment in forging as does the forging it represents. The size and location of the test-bar must be planned with a knowledge of the heating and forging practice to be employed. The amount of hot-working which it receives and the point in the forging sequence where this is done are very important. Only by careful planning can a localized test be representative of the whole forging. An error which occurred in the author's experience was to arrange for the tong-hold to be the test-coupon, and this was drawn out almost to finished size in the first heat. In the case of one batch of forgings so made, the test-coupon showed a very bad overheated fracture, though the forging itself was satisfactory, the reason being that the test-coupon had been shaped almost to finished size very early in the forging operation and had suffered two or three reheatings without extra work whilst the forging itself was being made. An ideal integral test-bar should, if possible, be located at the end opposite to the tong-hold and should receive its final work in the die impression; also, the amount of work given to it in the roughing stages should be as similar as possible to that given to the forging itself. It is therefore important that aircraft-engine manufacturers should consult the drop-forger fully when making fracture examinations on integral test-bars, and also when designing new parts carrying such integral test-bars.

A further consideration in the location of nicking is that it should be carried out transversely to the grain flow, since a comparison of fractures on the same overheated forging reveals that the transverse fracture is most sensitive to slight overheating, whereas the longitudinal fracture may hide its presence. From all the above remarks it is evident that a knowledge of forging practice is required when conducting a fracture examination for the presence of overheating.

With important forgings which do not carry integral test-bars, fracture tests on a percentage basis have in the past been carried out by some aircraft-engine manufacturers, but not by all drop-forgers. Such tests are costly and the information obtained from them has been insufficient to enable the metallurgist to discriminate between the various stages of overheating and burning, and no standards have been available for the comparison of fractures. When the overheating problem reached serious proportions, regulations were issued by the inspecting authorities which demanded fracture testing by the drop-forger on a percentage of representative samples. Where scrap forgings are available, they may be used for fracture tests provided that they are representative in thermal history of the batch concerned; where such forgings are not available, good ones must be fractured. It is only by such drastic means that overheating can be detected and held in check. It thus becomes the responsibility of the drop-forger to see that forgings are free from overheating, even when such forgings are heat-treated by the aircraft manufacturer or other user.

The next operation in the fracture test is the heat-treatment of the nicked forgings. In the past, forgings of different steels have been fractured in the normalized, hardened, and fully hardened and tempered conditions. At first some confusion existed as to the ideal condition in which to fracture the forgings. As experience was gathered and after the investigation referred to below, it became apparent that the best condition for the steel is that in which fracture takes place between the grains and not across them. The steel must be in both the strongest and the toughest condition, so that whilst the individual grains themselves resist fracture, some of the grain boundaries, by reason of their size and direction and the fact that they may be adversely affected by oxide or other inclusions, are more easily separated by the force applied. In the case of a steel in a softer condition, *e.g.*, in the normalized state, the grain boundaries, although affected by overheating, may yet be stronger than the grains, and hence fracture takes place along the cleavage planes of the grains, and a bright crystalline or silky or even fibrous fracture is obtained. This produces a flat and gives a confusing idea of crystal size, since fracture may quite easily take place across the short chords of even large grains, and furthermore, no evidence of oxide tints or films is then to be seen. A further disadvantage of the soft condition is that the fractures are apt to bend and shear, thus masking the true intergranular appearance. Again, in the case of a steel in the hardened condition, fracture is almost certain to take place "short," across the grains and not between them, thus masking the overheating unless it is of the gross variety. Most alloy steels for aircraft, both of the case-hardening type and others, attain a combination of maximum strength and toughness in the range 250–350 Brinell hardness number, and it has been found that this range is most suitable for detecting overheating by fracture tests. The ideal condition, of course, varies with different steels, and must to some extent be determined by previous experience; however, if the fracture is in any way fibrous or shows signs of shear, the hardness of the fracture test-piece must be increased by altering the heat-treatment. The actual heat-treatment given to a particular steel will naturally depend on its type. For instance, alloy case-hardening steels need a quenching treatment suited to the hardness range desired, which may not be that required by the specification. Again, in the case of the $4\frac{1}{4}\%$ nickel–chromium–molybdenum air-hardening steel, *S*28, the fracture test may be made in the normalized condition. However, all such alloy steels should be given the benefit of any preliminary heat-treatment normally carried out (such as refining or normalizing operations) before being brought into a suitable condition for fracturing, so that the steel may receive any refinement which such operations produce. From the foregoing remarks on the importance of correct heat-treatment for the fracture test, it is evident that where a large production of forgings is concerned, at least two heat-treatment furnaces with quenching equipment must be specially assigned to the treatment of the test-forgings. It is also important that the testing should be done without delay, so that the forge heating conditions may be adjusted immediately if necessary.

After heat-treatment, the forgings or integral test-coupons must be broken at the places nicked in order to reveal the fracture. In the past, various pieces of equipment have been used for this purpose. Very small forgings can be held in a vice and broken with a sharp hammer blow, or even in a fly press using a V-block and wedge. Larger forgings and full production inspection, however, call for a power press specially designed for the job. An air-operated press of 50 tons' capacity and having a fairly quick stroke was found ideal for the purpose. As fracture takes place rapidly the mechanism of the press was protected with an airdraulic safety attachment over the main cylinder. The press also needs to be well guarded on all sides, as the fractured pieces are liable to fly dangerously. V-blocks and wedges of various shapes and sizes may be required to deal with different forgings. Large forgings from which it is required to break off only a portion of the integral test-bar may demand special jigs on the press table. By whatever method the forgings are broken they should be broken quickly with the minimum number of blows (preferably one), since any shearing or tearing action affects the appearance of the fracture and may obliterate

FIG. 1.—Billet of Burnt Steel, showing disintegration after one hammer blow. × ⅓.

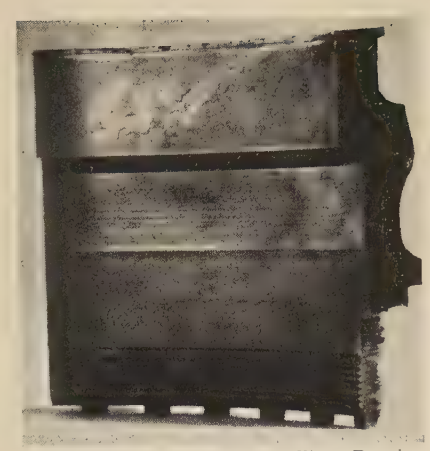


FIG. 2.—Typical Intercrystalline Burning Cracks revealed by magnetic crack detection on section of machined, upset, ring forging. × ½.

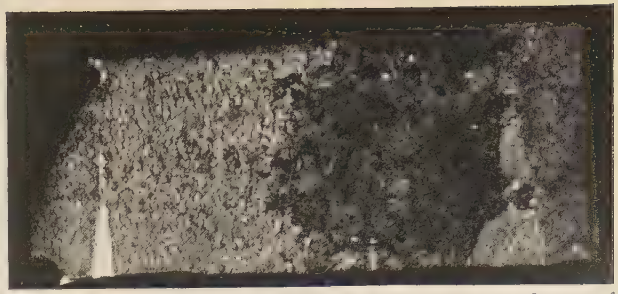


FIG. 5.—Fracture Test-Piece exhibiting acute roughness of "crozzled" skin adjacent to fracture. × 1.

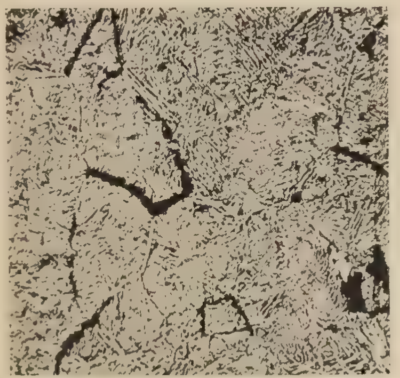


FIG. 3.—Burnt Mild Steel, showing large intercrystalline voids. Etched with 3% nital. × 25.

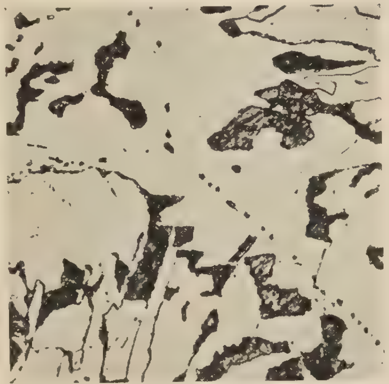


FIG. 4.—Burnt Mild Steel, showing coalesced globules at grain boundaries. Etched with 3% nital. × 500.

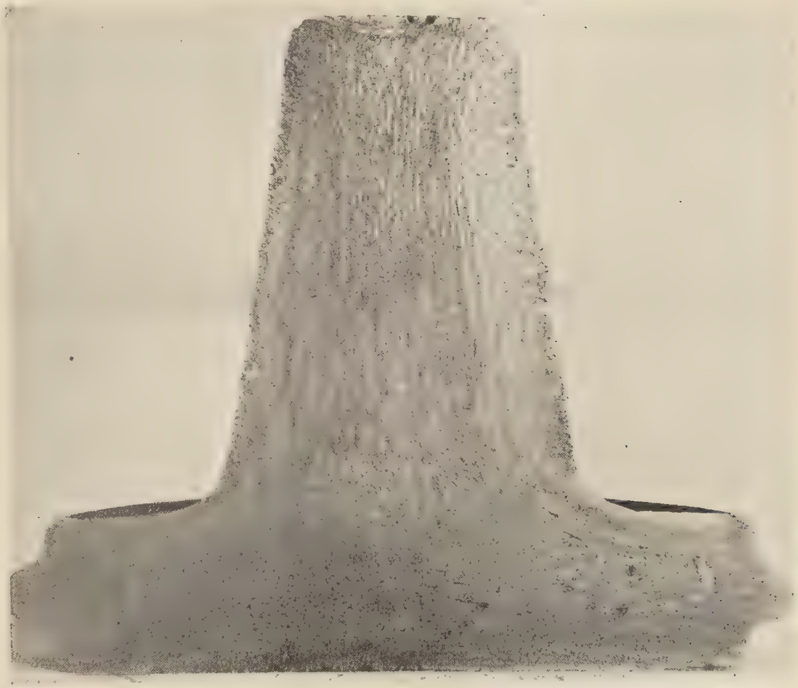


FIG. 6.—Macro-Etch of Upset Gear-Blank Forging, showing penetration of "crozzling" defect into forging. × 1.

[*Merchant.*

[*To face p.* 224 P.

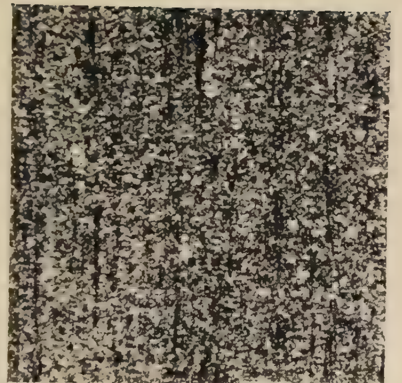


FIG. 7.—Control Sample, not heated, from as-rolled billet.

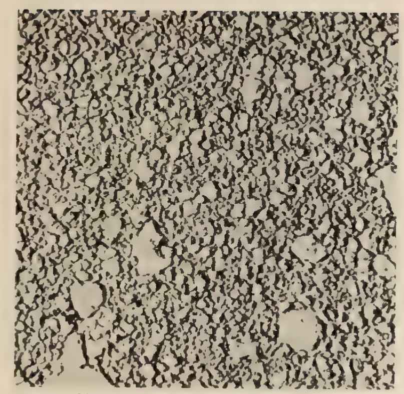


FIG. 8.—Heated at 1200° C.

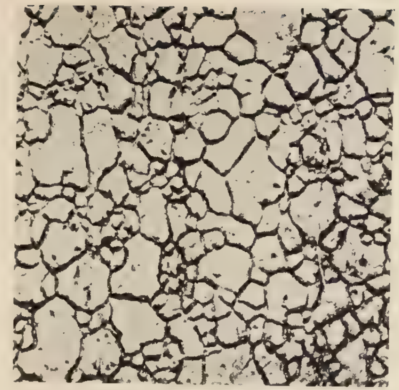


FIG. 9.—Heated at 1300° C.

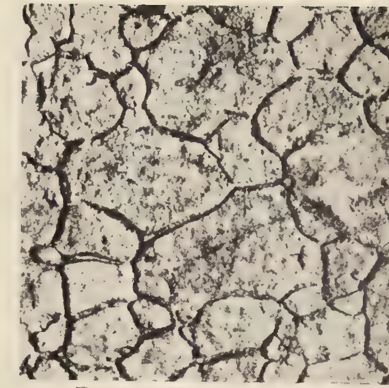


FIG. 10.—Heated at 1400° C.

FIGS. 7–10.—Surfaces of S82 (4¼% Nickel–Chromium–Molybdenum) Steel after soaking for ½ hr. at various temperatures. Surfaces prepared by etching with hydrochloric acid; oblique illumination. × 10.


FIG. 11.—Basic Open-Hearth S6 (Plain Carbon) Steel, showing fibre of steel persisting with signs of "crozzling" underneath.


FIG. 12.—Basic Open-Hearth Manganese–Molybdenum Steel (En 16), showing similar appearance to the steel in Fig. 11.

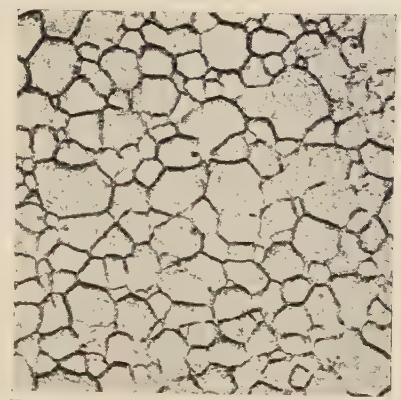


FIG. 13.—Basic-Electric S69 (3½% Nickel) Steel, showing clear and well-defined "crozzling."

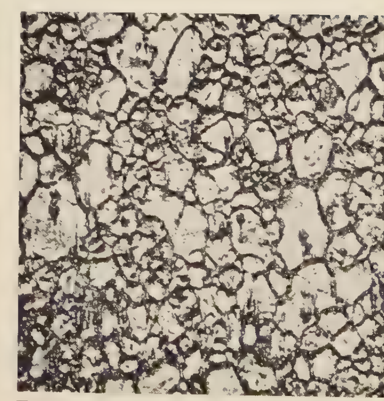


FIG. 14.—Basic Open-Hearth 4S11 (3¼% Nickel–Chromium–Molybdenum) Steel, showing more confused "crozzling."

FIGS. 11–14.—Surface of Various Aircraft Steels after Soaking for ½ hr. at 1300° C. Surfaces prepared by etching with hydrochloric acid; oblique illumination. × 10.

[*Merchant.*

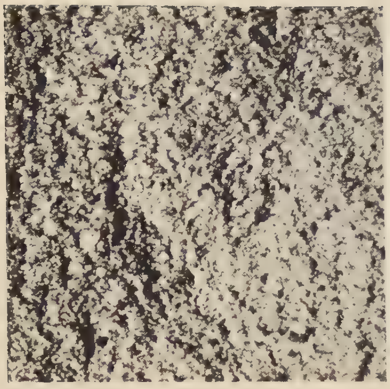


FIG. 15.—Control Sample, not heated. Fracture fibrous to silky. × 10.

FIG. 16.—Heated at 1200° C. Fracture showing small granular facets. × 10.

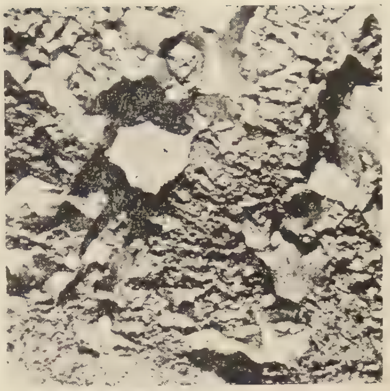


FIG. 17.—Heated at 1300° C. Fracture granular, with some large crystal facets. × 10.

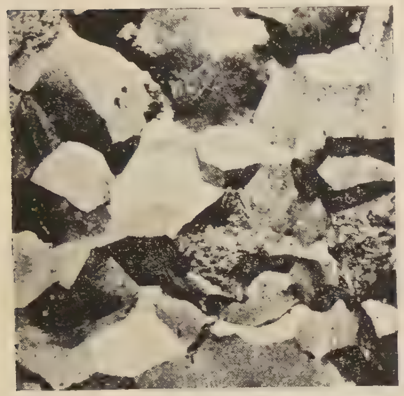


FIG. 18.—Heated at 1400° C. Fracture very coarsely granular. × 10.

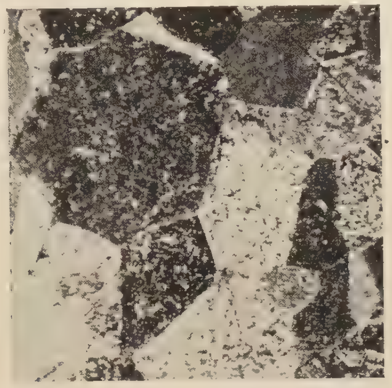


FIG. 19.—Microstructure of specimen heated at 1400° C. Etched with 3% nital; oblique illumination. × 10.

FIG. 20.—The same specimen as in Fig. 19, revealing twinned nature of the austenite. Etched with 3% nital. × 20.

FIGS. 15–20.—Fractures and Microstructure of Basic-Electric *S*82 ($4\frac{1}{4}$% Nickel–Chromium–Molybdenum) Steel after Soaking at Various Temperatures for $\frac{1}{2}$ hr.

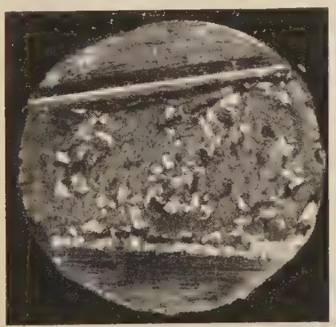


FIG. 21.—Before Reclamation Treatment, showing granular fracture.

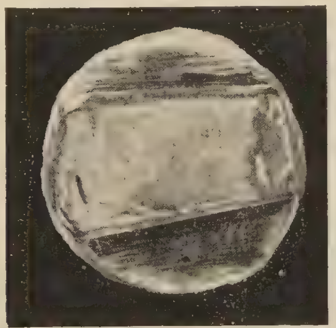


FIG. 22.—After Reclamation Treatment, showing fibrous fracture.

FIGS. 21 and 22.—Transverse Fracture Tests on Overheated *X*4340 Steel ($1\frac{3}{4}$% Nickel–Chromium–Molybdenum) before and after special reclamation treatment. Approximately actual size.

[*Merchant.*

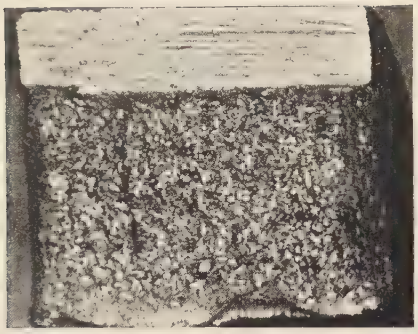


FIG. 23.—Overheated only. Brinell hardness number 201. Bright crystalline fracture which occurred across the grains and to a large extent masks the true crystal size.

FIG. 24.—Overheated and Normalized. Brinell hardness number 207. Fracture of dull grey fibrous texture which broke flat and showed no trace of large crystalline facets.

FIG. 25.—Overheated, Normalized, and Refined. Brinell hardness number 388. Fracture: Silky grey and exhibiting a few dull grey crystal facets.

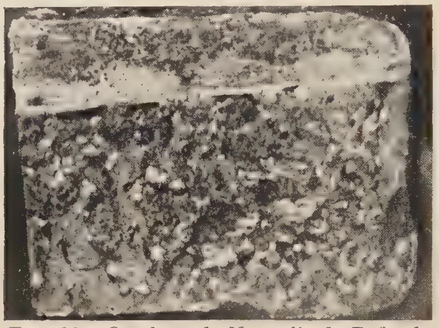


FIG. 26.—Overheated, Normalized, Refined, and Hardened. Brinell hardness number 331. Fracture: Dull grey mat, with large granular facets plainly visible.

FIGS. 23–26.—Transverse Fractures of S90 (5% Nickel Case-Hardening) Steel. Approximately actual size.

FIG. 27.—Overheated only. Brinell hardness number 293. Level fracture of bright mat crystal facets, indicating some masking of the true crystal grains.

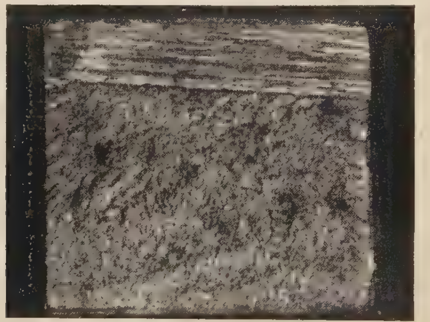


FIG. 28.—Overheated and Normalized. Brinell hardness number 321. Dull grey fibrous fracture, showing no sign of large crystal facets.

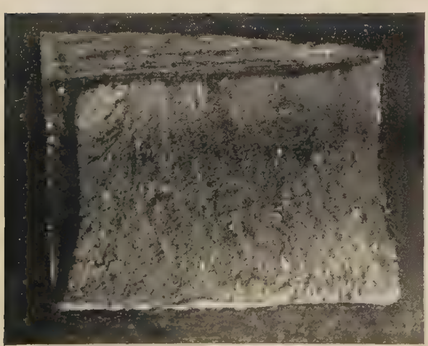


FIG. 29.—Overheated, Normalized, and Hardened. Brinell hardness number 444. Fracture similar in texture to that of the normalized condition, but matrix finer; only one or two small crystal facets visible.

FIG. 30.—Overheated, Normalized, Hardened, and Tempered. Brinell hardness number 341. Dull grey mat fracture with large granular facets plainly visible.

FIGS. 27–30.—Transverse Fractures of En 24 ($1\frac{1}{2}$% Nickel–Chromium–Molybdenum) Steel. ×1 (approx.).

[*Merchant.*

FIG. 31.—Satisfactory Fracture, transverse section. No evidence of crystal facets.

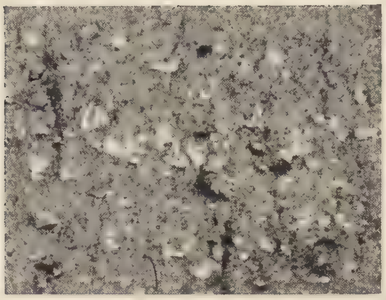


FIG. 32.—Overheated (Acceptable) Fracture, transverse section. Small crystal facets evident.

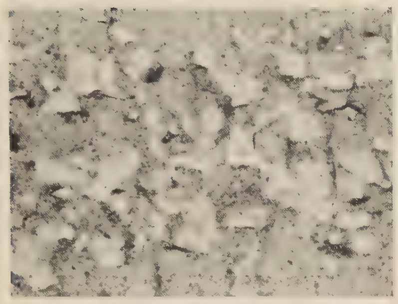


FIG. 33.—Overheated (Borderline) Fracture, transverse section. Mat granular facets in 50% of the fracture.

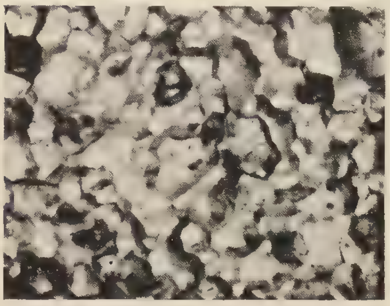


FIG. 34.—Severely Overheated Fracture, transverse section. The fracture consists entirely of mat granular facets, sometimes with oxide colorations.

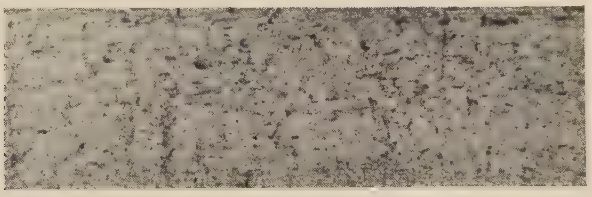


FIG. 35.—Longitudinal Fracture from Overheated (Acceptable) Standard. The effect of the longitudinal fibre exceeds that of the small crystal facets evident in the transverse fracture.

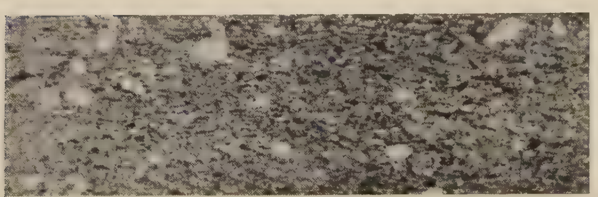


FIG. 36.—Longitudinal Fracture from Overheated (Borderline) Standard. The effect of the granular facets in this standard exceeds that of the longitudinal fibre, thus confirming that the steel has been overheated to a doubtful degree.

FIGS. 31-36.—Standard Fractures of *S*82 ($4\frac{1}{4}$% Nickel–Chromium–Molybdenum Case-Hardening) Steel for Detection of Overheating. × 2. (*See* Table I. for treatment and properties.)

[*Merchant.*

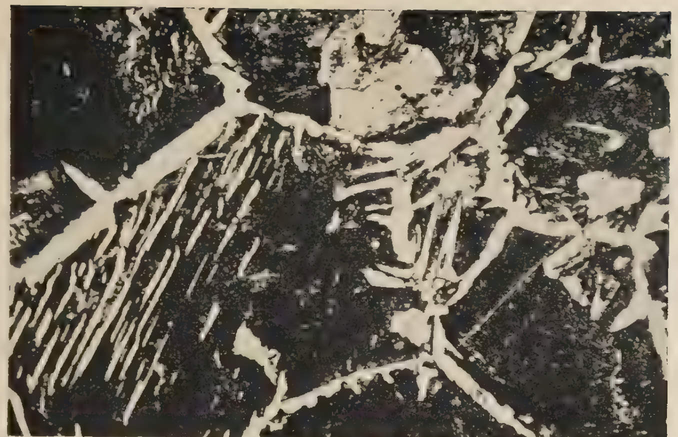


FIG. 37.—Microstructure of S6 (0·4% Carbon) Steel Overheated in Forging, showing large grains and angular off-shoots of ferrite. Etched with 3% nital. × 250.

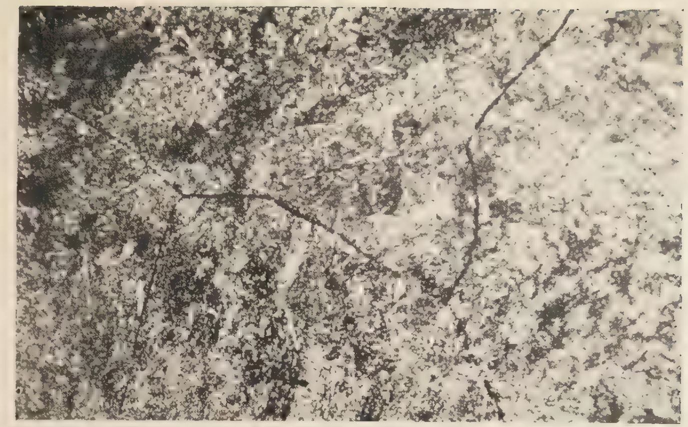


FIG. 38.—Microstructure of En 24 (1½% Nickel-Chromium-Molybdenum) Steel Overheated in Forging, showing dark grain-boundary indications. Etched with 10% sulphuric and 10% nitric acids in water. × 100.

FIG. 39.—Control Sample, not overheated, from billet as rolled.

FIG. 40.—Heated at 1200° C.

FIG. 41.—Heated at 1300° C.

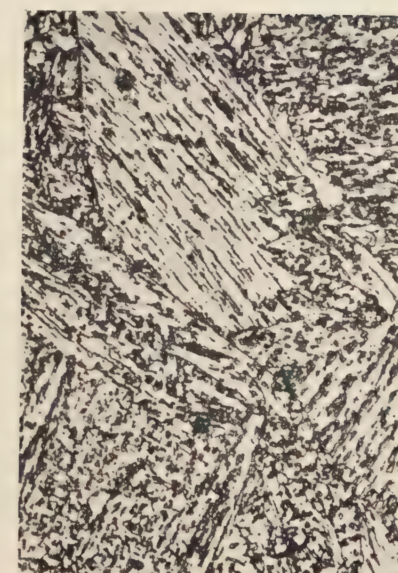


FIG. 42.—Heated at 1400° C.

FIGS. 39–42.—Microstructures of S90 (5% Nickel Case-Hardening) Steel after soaking at various temperatures for ½ hr. Etched with 3% nital and electrolytically polished. × 250

the granular form produced by the less severe stages of overheating.

After fracturing, the forgings must be examined by a metallurgist or inspector competent to judge them. Early in the epidemic of overheating, this phase of the test gave rise to varying opinions, and a definite need existed for standards of overheated fractures. Some authorities used low-power microscopes for the examination, while others were content with examination by the unaided eye. Fracture characteristics are very much a matter of personal impression, and loose phrases are often used in describing them. It was for this reason that an endeavour was made to create a set of fracture standards as related below. Whilst on this subject one may say it is preferable for actual standard fractures to be used by the inspectors rather than photographs, since the latter cannot indicate clearly the three-dimensional nature of the facets present. For preserving fractures of overheated steel, tin-foil carefully pressed on to the fracture is more satisfactory in preventing rust than lacquering, which often spoils the true appearance of those which are slightly granular. For the examination of fractures, especially those showing slight overheating, a low-power binocular microscope, preferably with magnifications up to 20 and having good oblique illumination, is desirable. Hand lenses or simple bench magnifiers are unsatisfactory and tiring to the eyes when many fractures have to be examined. A binocular microscope enables a stereoscopic view of the fracture to be obtained, and thus gives a true enlargement; such an instrument is essential to detect any oxide colours or tints that may be present on the crystal facets of severely overheated steel.

Experimental Work.

In the early stages of this investigation of overheating in alloy steels, experimental work was carried out in an attempt to correlate the surface appearance after etching with the fracture examination and also with any changes in the microstructure and static physical properties of the steel. Some results on a cast of basic-electric 4¼% nickel–chromium–molybdenum steel, *S*82, were most interesting; the results of the surface examination have already been reported under that section, and the fracture examination will be described below. The samples of this steel were overheated for ½ hr. at 1200°, 1300°, and 1400° C., and a control sample (*i.e.*, one not overheated, from the rolled billet) was also run for comparison purposes. After overheating, the samples were slowly cooled, then hardened by oil-quenching from 760° C., and stress-relieved at 180° C. The resultant Brinell hardness number was 402, and the samples were fractured transversely in this condition. The fractures were examined and photographed under oblique illumination at a magnification of 10; Figs. 15, 16, 17, and 18 refer to the control sample and the samples overheated at 1200°, 1300°, and 1400° C., respectively. Visually, the fractures could be described as follows:

Control sample . .	Fibrous to silky.
Overheated at 1200° C.	Slightly granular.
Overheated at 1300° C.	Granular, with some large crystal facets.
Overheated at 1400° C.	Very coarsely granular with oxide tints or films on the crystal facets.

The oxide tints or films on the crystal facets of severely overheated specimens are often only to be observed on a freshly fractured specimen, and appear to fade with time. The results of the surface examination of these samples are shown in Figs. 7, 8, 9, and 10, respectively, and it will be seen that a more or less complete correlation of the surface grain-size with the fracture grain-size was obtained. The grain-sizes of the pickled surfaces were measured, with the following results:

Treatment.	No. of grains/sq.in. × 10.	Equivalent A.S.T.M. Grain-Size No.
Control sample . .	Approx. 5000	Approx. 7
Overheated at 1200° C.	,, 300	,, 2–3
Overheated at 1300° C.	,, 50	,, 0
Overheated at 1400° C.	,, 8	,, −3

As the crozzled skin can be taken as an indication of the grain-size of the steel at the maximum temperature to which it is heated, it will be seen that a steel of comparatively fine grain-size is transformed to one of comparatively coarse grain-size on heating to the normal forging temperature of 1200° C., and becomes a great deal coarser as the temperature is increased above this. Etched microspecimens from the sample overheated at 1400° C. showed large grains quite visible to the unaided eye, and in order to confirm that the crozzled-skin grain-size could be correlated with the internal grain-size (in the absence of work), a photograph of this particular microsection was taken under oblique illumination, at 10 magnifications (Fig. 19). Oblique illumination was found useful at this magnification in that it revealed the differing orientations of the large grains. Although it is difficult to assess the grain-size of a granular fracture because of its three-dimensional nature, a comparison of Figs. 10, 18, and 19 shows good agreement. For the sake of interest, Fig. 20 is included which was taken from the same microsection as Fig. 19, and reveals the twinned nature of the coarse austenitic grains.

In order to determine which condition would be most sensitive to the detection of overheating by the fracture test, samples of two aircraft steels were overheated and fractured in various conditions approximating to those produced by the commercial heat-treatments normally given to the

steels. Both were alloy steels, one being the well-known case-hardening 5% nickel steel, *S*90, and the other being the $1\frac{1}{2}$% nickel–chromium–molybdenum steel, En 24. The analyses of these steels are :

	C, %.	Si, %.	S, %.	P, %.	Mn, %.	Ni, %.	Cr, %.	Mo, %.
*S*90	0·13	0·25	0·018	0·025	0·39	5·10	0·20	0·19
En 24	0·40	0·20	0·020	0·030	0·69	1·79	0·95	0·25

Transverse fractures were conducted as these are more sensitive to overheating. Samples of the two steels were first forged from rolled billets to test-bars approximately $2 \times 1\frac{1}{2}$ in., the maximum heating temperature for forging being 1200° C. The bars were then overheated by soaking for 1 hr. at 1350° C., and then air-cooled. The heat-treatments carried out were those which are usually given to the steel in practice, *viz.*, normalizing at 900° C., refining by oil-quenching from 850° C., and hardening by oil-quenching from 760° C. for the case-hardening steel, and normalizing at 880° C., hardening by oil-quenching from 850° C., and tempering at 570° C. for the nickel–chromium–molybdenum steel. The steels were fractured in all these conditions and also in the overheated condition. In addition, the Brinell hardness was measured. Photographs of the resulting fractures are shown in Figs. 23 to 26 for the *S*90 steel and in Figs. 27 to 30 for the En 24 steel. In the overheated condition, the fractures were crystalline but more or less flat and level; fracture had occurred across the grains and this had to some extent masked the true crystal size. In the normalized conditions, dull grey silky-to-fibrous fractures were obtained, with no trace of crystalline facets. In the fully hardened or refined conditions the fractures were similar to those of the normalized condition, except that the matrix of the fracture was finer and more inclined to be silky and contained a small proportion of dull grey crystal facets. In the case of the *S*90 steel the correct condition for fracture was that produced by the commercial treatment of oil-quenching from 760° C., in which condition the fracture exhibited large mat granular facets. In the case of the En 24 steel the correct condition for fracture was the hardened and tempered state, which possessed the best combination of strength and toughness, and here again the fracture showed a large proportion of mat granular facets. It would thus appear that the final heat-treated condition usually applying to the steel in correct practice is the most suitable for fracture examination. It should be noted that although normalizing preceded hardening in this investigation, it is not necessary in heat-treating for the fracture test, except in so far that it is advisable to give the steel the benefit of any such refining heat-treatment. In this respect also, case-hardening steels deserve any benefit which accrues from a blank carburizing treatment, as it is known that carburizing treatments help to refine a coarse overheated structure if the overheating has not been too severe.

Fracture Standards.

Early in this investigation of overheating, the establishment of fracture standards appeared to be most desirable. Although it was understood and generally agreed both by drop-forgers and users that material showing even slightly granular fractures was to some extent overheated, there was a definite need at the time to use such material, provided that it could be proved satisfactory for the purpose intended. The establishment of fracture standards for overheating necessarily involves consideration of the effects of overheating on the mechanical properties of the steel. At the time, the need for such standards was urgent and this, to a large extent, precluded fatigue tests, which are necessarily of long duration; in particular such tests had to be excluded because any reduction of the fatigue strength caused by overheating has been shown to be very erratic [2] and so a very large number of tests would have been necessitated. The course adopted in the emergency which prevailed was to prepare a set of fracture standards by overheating to various controlled degrees, and then to measure the static mechanical properties. Overheating reduces the impact and ductility values considerably, although perhaps not below specification requirements. The degree of overheating which caused a reasonable reduction of these properties, say, 20% below the average for correctly treated material, was taken as the standard. Material having a fracture superior to that on the standard was acceptable, and that having a worse fracture was rejected. In borderline cases, forgings could be sectioned at selected locations for tensile tests which were correlated with the control test-bars of the cast, the latter having been heated and forged under conditions not likely to produce overheating. Another basis on which to assess an acceptable fracture is the difference between the transverse and longitudinal fractures. The former are more sensitive to overheating, which in its mild stages does not affect the longitudinal fracture; but at a certain stage in overheating, the granular facets make their appearance in the longitudinal fracture, and there would appear to be some logic in arguing that when the facets do not show in the longitudinal fracture, the steel is acceptable from the point of view of the fracture test. When facets do show in the longitudinal fracture, overheating is present in the steel to a degree which nullifies the extra qualities imparted to the steel by its longitudinal grain or fibre. Thus the tensile properties of such a steel would probably be depressed at least approximately to the

same extent as is occasioned by transverse fibre, which is often considerable in the directions of ductility and impact resistance.

In preparing a set of fracture standards it was considered necessary to make a set for each type of alloy steel used for the most important aero-engine parts, and it was desirable where both basic open-hearth and electric steels were used to make standards from both types of steel. Typical standard fractures proposed for a $4\frac{1}{4}\%$ nickel–chromium–molybdenum case-hardening steel, *S*82, are shown in Figs. 31 to 36, and the results of mechanical tests carried out on these standards are given in Table I. In preparing these standards, flat test-bars $3 \times 1\frac{1}{2}$ in. thick were carefully forged so as to be free from overheating. This shape of test-bar was used in order to be able to make longitudinal fractures, in addition to the usual transverse fracture. The bars were then heated for 1 hr. at various temperatures above the recognized safe maximum, cooled in air, and heat-treated as indicated in Table I. All bars were so treated in triplicate. Four standards or degrees of overheating were then selected according to the granular nature of the fractures. The standards selected were as follows:

(a) *Satisfactory* (*Fig.* 31).—The fracture and mechanical properties of this standard are ideal; the three mechanical tests show a fair degree of uniformity.

(b) *Overheated* (*Acceptable*) (*Fig.* 32).—This fracture shows a proportion of small mat facets, which have had the effect of very slightly reducing the elongation, reduction of area, and Izod impact values.

TABLE I.—*Mechanical Properties of Fracture Standards of* $4\frac{1}{4}\%$ *Nickel–Chromium–Molybdenum Steel* (S82).

Analysis.—C 0·17%, Si 0·25%, S 0·019%, P 0·030%, Mn 0·40%, Ni 4·06%, Cr 1·23%, Mo 0·33%.

Heat-Treatment.—Refined: $1\frac{1}{2}$ hr. at 830° C., O.Q. Hardened: $1\frac{1}{2}$ hr. at 760° C., O.Q. Tempered: 3 hr. at 180° C.

Longitudinal properties of test-pieces from flat test-bars $3 \times 1\frac{1}{2}$ in. section.

Standard.	Fig. No.	Yield Point, tons/sq.in.	Tensile Strength, tons/sq.in.	Elongation on 2 in., %.	Reduction of Area, %.	Average Izod Impact Strength,* ft. lb.	Brinell Hardness No.
Satisfactory	31	89·9 88·5 91·3	93·1 92·0 92·4	14·0 15·0 15·0	54·0 62·0 51·0	43·0 43·0 44·0	415 415 415
Average		...	92·5	14·6	55·6	43·6	...
Overheated (acceptable)	32	89·0 88·9 91·3	92·7 92·7 92·4	14·0 14·0 15·0	62·0 50·0 45·0	46·0 36·0 43·0	415 429 415
Average		...	92·6	14·3	52·3	41·6	...
Overheated (borderline)	33	92·0 84·9 83·8	93·6 87·4 94·2	15·0 11·0 10·0	48·0 56·0 35·0	36·0 40·0 32·0	415 388 429
Average		...	91·7	12·0	46·3	36·0	
Severely overheated	34	... ...	89·2 91·7	4·0 2·0	10·0 6·0	21·0 22·0	444 429
Average		...	90·45	3·0	8·0	21·5	...
Specification value		...	85·0 min.	12·0 min.	...	25·0 min.	...

* 120-ft. lb. machine; British Standard round test-piece.

(c) *Overheated* (*Borderline*) (*Fig.* 33).—This fracture exhibits a considerable proportion of mat granular facets, and these have had the effect of depressing the ductility and impact values by about 20%; the erratic nature of the three tests should be noted.

(d) *Severely Overheated* (*Fig.* 34).—This fracture consists entirely of large granular facets, the effect on the mechanical properties being to depress the ductility and impact resistance to a degree which makes acceptance of steel having such a fracture impossible. There was

also a slight fall in the tensile strength, and the yield points could not be observed; this fact, together with the very low elongation values, suggests that failure might have taken place actually within the elastic range.

Longitudinal fracture tests were conducted on the acceptable and borderline fractures and the results are shown in Figs. 35 and 36 respectively. In the former, the deleterious effect of the small crystal facets is not strong enough to interrupt the longitudinal fibre, and thus this standard is an acceptable one. In the case of the borderline fracture, the effect of the mat granular facets has overcome any superior longitudinal-fibre properties, and it is considered that this represents a doubtful and dangerous condition which should not be accepted for such high-duty applications as aero-engine components.

When these standards were being prepared, note was taken of the furnace temperatures and conditions which were used to produce them. The four standards depicted in Figs. 31 to 34 were produced by heating for 1 hr. at temperatures of 1150°, 1300°, 1350°, and 1400° C. respectively in a pulverized-fuel-fired forge furnace normally used for production. Temperatures were measured by an optical pyrometer with the furnace flame turned down, and were also checked by periodic immersions of a rare-metal thermocouple fitted with an indicator. However, it must be emphasized that furnace types and conditions may well differ from plant to plant, and therefore the temperatures stated bear accurate significance only with regard to the fractures shown for the particular conditions used. From the point of view of preventing overheating by controlling the maximum temperature to which the steel is heated and by the use of fracture standards, it is desirable that each plant should in the first instance produce its own standards, which can afterwards be adjusted to the user's standard, or any other standard which may be prepared.

(3) *Metallographic Examination.*

The microstructures of overheated and burnt plain carbon steel are familiar to most metallurgists. That of burnt steel has already been referred to (*see* Figs. 3 and 4). Overheating is detected in the microstructure of plain carbon hypo-eutectoid steels as ferrite envelopes outlining the transformed austenitic grains, and frequently the degree of overheating can be assessed from the size of these grains and from the acicularity of the ferrite off-shoots which often penetrate the grains. Fig. 37 shows the microstructure of a 0·40% carbon steel, *S*6, which has been overheated in forging. Such plain carbon steels will usually respond, however, to the normal methods of heat-treatment, after which little, if any, evidence of overheating remains either in the structure or in the properties. The microstructures of overheated and burnt alloy steels which do not respond fully to normal heat-treatment are by no means as clear. Austin's work on burnt alloy steels [2] described how a special etching reagent consisting of an aqueous solution of 10% nitric acid and 10% sulphuric acid was used to detect burning or overheating in the form of dark markings more or less outlining the austenitic grains, which were then shown to be similar in size to the mat crystals revealed by the fracture. Fig. 38 illustrates this type of structure in an overheated specimen of a $1\frac{1}{2}$% nickel–chromium–molybdenum steel, En 24. When Austin's work was published, a good deal of discussion took place both on the relative merits of such a strong etch, and on the theories advanced to account for the particular intergranular effect. It was generally agreed that the detection of burning was most difficult without the use of special etching reagents, and the nearest approach to anything definite in the very lightly etched microstructure of burnt alloy steel was the appearance of chains of very minute particles "with possibly larger particles at the cross-roads" (grain-boundary junctions). It was suggested that such particles were not normal inclusions in steel and might conceivably be the results of gas evolution which had occurred as the temperature of the steel increased. It is not proposed to discuss the theory of the mechanism of overheating and burning in alloy steels at this stage; the interested reader is advised to consult Austin's paper [2] and also the discussion on it. However, from the point of view of the detection and confirmation of overheating, the subject of the strong etching reagents and their effect on the steel is more interesting. Since the publication of the above-mentioned work, the aqueous acid solution has been fairly widely used on prepared microspecimens for the detection of overheating. Some metallurgists hold the view that the test does not operate with the 3% chromium–molybdenum steel, D.T.D. 306. In any case, the test must be carried out on an internal section of the steel. Whilst it is possible to do this with many large forgings which carry integral test-bars, and others where a microsection can be sawn off or conveniently trepanned from a hole, the test is clearly not applicable to smaller forgings. The crozzling phenomena would impede examination of the surface, unless the latter had been removed by machining, and in any case the results would not be representative of the steel generally.

The use of this particular etching reagent appears to require care. It is used cold, but at least three, if not more, 30-sec. periods of etching are required, in between which the surface being etched must be cleaned with cotton-wool under

running water and then dried; finally, it is advisable to repolish the surface lightly with a chromic oxide pad, and again wash and dry the specimen before it is examined. Microscopic examination is usually carried out at 100 magnifications. It need hardly be mentioned that the use of this reagent completely obliterates any other details of the structure, except at the boundaries of the austenitic grains present when overheating has occurred. Here it must be stated that what appears to be an exaggerated condition is produced. The reason for this statement emerges from some experience in the examination of overheated alloy steels which have been polished electrolytically, and then etched in the usual manner with 3% nital. By its nature, electrolytic polishing removes metal from the surface of a specimen in an ideal way, and gives a structure free from any surface irregularities such as may be present with mechanical polishing, or which might be inhibited by surface-tension effects of strong acid reagents. In overheated alloy steels, the intergranular films, voids, flowed inclusions, or whatever they may be, must necessarily be ultra-small if they cannot be observed in the unetched microsection. It is therefore quite likely that no matter how carefully the final mechanical polishing is carried out, the resultant distorted layer will hide such ultra-thin films. Electrolytic polishing has been used by the author with success to reveal what appear to be films at the grain boundaries of the original austenite grains. Figs. 39 to 42 show photomicrographs of sections of a 5% nickel case-hardening steel, *S*90, in different states of overheating. Fig. 39 represents a control sample of the steel (not overheated and in the as-rolled condition) and Figs. 40 to 42 show samples of the steel after overheating for ½ hr. at temperatures of 1200°, 1300°, and 1400° C., respectively. The increasing size of the austenite grains and the accompanying increase in the acicularity of the carbides or the size of the austenite twins with increase in temperature, are well marked, together with the "grain-boundary indications." These photomicrographs were taken with the steel in the untreated condition after overheating, but the films at the grain boundaries are revealed by careful electrolytic polishing when in the hardened condition, and this is the case also with other common alloy steels. It was observed that such films were always extremely thin when correctly polished, and a magnification of 500 is best suited to their detection. As the usual action of electrolytic polishing is to accentuate any discontinuities in the surface, it is likely that the films themselves are extremely thin, so thin, in fact, that they cannot be seen at the highest magnifications on unetched specimens. The present photographs were taken at magnifications of 250 to show the nature of the increasing grain-size.

The use of metallographic examination for the detection of overheating must at present be more or less strictly confined to confirmation of the results of other tests, such as fracture, &c. It is not practicable as a routine check because of the fact that overheating may be local, and also the surface-crozzling phenomenon interferes with it; and its use on integral test-coupons must be restricted to those which have been correctly designed and made to represent the conditions of the forging.

(4) *Mechanical Tests.*

Apart from the work of Austin (*loc. cit.*) very little information has been published on the mechanical properties of overheated alloy steels. Since that work was published, the drop-forging industry has heard complaints from time to time of a reduction in fatigue strength in forgings, although satisfactory static mechanical properties have been obtained. There is no doubt that the fatigue limit of steel is considerably reduced by severe overheating or burning, but that of steel in the less severe states of overheating needs some investigation, especially when it is considered that such a state is perhaps not the result of negligence or lack of control on the part of the drop-forger. To reject such steels in the slightly overheated condition because tests on other steels in perhaps a different and far worse state of overheating have shown poor or erratic fatigue values, is to invite criticism, especially if the static mechanical properties on which the steel is normally bought and sold are maintained at a fair margin above the minimum specification requirements.

Static Mechanical Properties.

The author's experience on the static mechanical properties of overheated alloy steel can be generalized in the following statement, which is based on results and observations from a large number of tests on different types of steels, some typical values of which are given in Table I. for a cast of 4¼% nickel–chromium–molybdenum case-hardening steel, *S*82.

(a) *Satisfactory Steel.*—Provided that heat-treatment conditions are uniformly controlled, a high degree of uniformity should prevail in the test results obtained from specimens heat-treated in different batches but belonging to the same cast.

(b) *Slightly Overheated Steel.*—Provided that there are control tests (made on test-bars forged under ideal conditions) to which reference can be made for any particular cast, slightly overheated steel is revealed in the slightly reduced values of elongation, reduction of area, and impact-resistance obtained in the mechanical tests. These reductions are not usually more

than approximately 5% and are best seen in the reduction-of-area test.

(c) *Overheated Steel.*—With the same provisions as for slightly overheated steel, the ductility and impact-resistance values for overheated steel may show considerable reductions, perhaps up to 20%, below those expected and given by control tests on specimens free from overheating. The properties may still be above the minimum specification requirements, but this borderline condition is a very doubtful one and can really be clarified only by a series of fatigue tests carried out on specimens in such a condition. This stage may be accompanied by a more or less brittle type of fracture.

(d) *Severely Overheated Steel.*—In this case all the static mechanical properties may be affected except the hardness. The ductility and impact resistance may be reduced to very low values, and failure may actually take place within the elastic range, thus reducing the ultimate tensile strength and eliminating the yield point if the overheating is very severe. In such a case the recording and examination of the load/elongation curves should prove interesting. This stage is almost certain to be accompanied by a brittle, rather than a ductile, type of fracture.

In preparing the fracture standards for the $4\frac{1}{4}$% nickel–chromium–molybdenum steel, *S*82, mentioned above, test-bars were overheated at various temperatures, but only four of these were selected as standards. In addition, control tests were carried out on bars not overheated but heat-treated with the overheated samples at the same time. On all these bars mechanical tests were made in triplicate. Some of the mechanical-test results for the selected standards have already been given in Table I., and the average elongation, reduction of area, and Izod impact values are shown graphically in Fig. 43 for the whole series of tests. It will be seen that up to 1350° C. the curves for reduction of area and impact resistance follow each other closely, and that both these properties and the elongation commence to fall off seriously only when 1300° C. is passed. An interesting feature was the slight but definite increase in the reduction of area and impact resistance on heating at normal forging temperatures, *i.e.*, approximately 1200° C.

Fatigue Properties.

Fatigue tests were carried out on a well-known aircraft alloy steel, *S*90 (5% nickel case-hardening steel), in order to determine the effect of overheating in drop-forging within the limits in which it might occur owing to lack of furnace-temperature control or excessive time at high temperatures. For this latter purpose it was considered that soaking for $\frac{1}{2}$ hr. at these temperatures would normally cover such eventualities. The samples were prepared from a basic-electric cast of $1\frac{1}{4}$-in. sq. billets of the following analysis:

C, %.	Si, %.	S, %.	P, %.	Mn, %.	Ni, %.	Cr, %.	Mo, %.
0·14	0·17	0·031	0·012	0·30	5·00	0·27	0·14

Four sets of specimens were prepared:

(1) As-rolled (control samples, not overheated).
(2) Heated for $\frac{1}{2}$ hr. at 1200° C. and air-cooled.
(3) Heated for $\frac{1}{2}$ hr. at 1300° C. and air-cooled.
(4) Heated for $\frac{1}{2}$ hr. at 1400° C. and air-cooled.

The samples were then machined to $\frac{15}{16}$ in. dia., refined for 1 hr. at 850° C. and air-cooled, and hardened by oil-quenching after 1 hr. at 760° C.

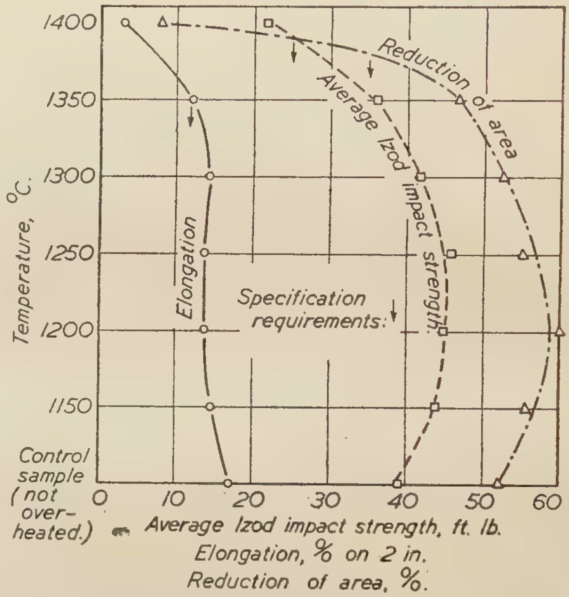


FIG. 43.—Ductility and Impact Resistance of *S*82 Steel Overheated at Various Temperatures (*cf.* Table I.).

Figs. 39 to 42 show photomicrographs of these samples in the overheated condition and reflect the increasing grain-size which occurs with rising temperature. The fatigue tests were carried out on a Haigh testing machine (alternating direct stress) on the basis of 10 million reversals with a zero mean stress. Test results obtained are shown in Table II. It will be observed that although there is an appreciable reduction in the ductility and impact resistance of the sample heated at 1300° C., the fatigue strength is not impaired. The low fatigue value of the sample heated at 1200° C. is considered to be at least partly attributable to experimental error, since this is a normal forging temperature for this steel, although the test-bars on which these results were obtained were not hot-worked after overheating. The fatigue strength of the sample heated at 1400° C. shows a considerable reduction, which might cause premature failure in highly stressed parts, especially

TABLE II.—*Mechanical Properties of 5% Nickel Steel* (S90) *Overheated at Various Temperatures.*

$1\frac{5}{8}$-in. dia. test-piece refined at 850° C. and oil-hardened at 760° C.

	Specification Requirements.	Control Sample.	Samples Overheated for ½ hr. at :		
			1200° C.	1300° C.	1400° C.
Yield point, tons/sq.in.	...	76·0	75·4	78·0	77·2
Maximum stress, tons/sq.in.	65 min.	77·6	77·0	79·2	79·8
Elongation on 2 in., %	13 min.	16·0	15·5	13·0	12·0
Reduction of area, %	...	55·0	53·0	47·0	40·0
Izod impact strength, ft. lb.	30 min.	49, 53, 52 (51·3)	48, 50, 52 (50·0)	40, 41, 42 (41·0)	36, 37, 40 (37·6)
Brinell hardness number	...	341	341	341	341
Appearance of fracture	...	Satisfactory.	Satisfactory; no evidence of over-heating.	Showed evidence of mat crystal facets indicative of slight over-heating.	Showed evidence of large mat crystal facets indicative of over-heating.
Fatigue limit,* tons/sq.in.	±31 min.†	35·3	33·0	35·1	32·3
Fatigue ratio ‡	47·7	45·5	42·8	44·3	40·4

* At 10^7 cycles; mean stress = zero; Haigh machine.
† Usual accepted value for this steel under conditions stated.
‡ Percentage of tensile strength.

if such parts were heat-treated close to the lower limit of the specified maximum stress.

These tests were undertaken to cover what were considered to be eventualities in production at the particular plant in question, *i.e.*, accidental heating for periods of up to ½ hr. at temperatures exceeding those normally used in pulverized-fuel-fired forge furnaces. The fatigue results obtained may not be indicative of those to be expected from the same type of steel overheated under other conditions, and especially if soaked for a longer time at the highest temperature, namely, 1400° C.

To sum up the effect of overheating on the fatigue strength of alloy steel, one can say that it would appear that this is only impaired when the ductility and impact resistance are appreciably lowered below the expected or normal values, and when an approach is made towards a brittle, instead of a ductile, type of fracture.

Methods of Preventing Overheating and Reclaiming Overheated Alloy Steels.

Prevention of Overheating.

In order to prevent overheating, one must understand the causes, *i.e.*, such factors as temperature and time of heating, furnace atmosphere, type of furnace, and amount of hot work given to the forging in its various stages of production. It may be stated that if a piece of steel is heated quickly and uniformly to its normal forging temperature and then forged immediately so that even the largest section of it receives a reasonable amount of work, no overheated structure will occur. This ideal is not easy to obtain in practice, and in Britain various factors have combined to militate against it. The type of furnace which has commonly been used for drop-forging has not been of the best design. Generally, furnaces have been too small and badly fired, thus making uniformity of temperature practically unattainable. In pre-war days, oil fuel was favoured, but war conditions necessitated to a large extent a return to gas and pulverized fuel. Whilst gas and oil fuel can be ideal if sufficiently pure and clean and properly fired, pulverized fuel has provided many difficulties in the shape of non-uniformity of temperature and the slagging of the ash which takes place on the hearth floor of the furnaces if the melting point of the ash is at all low. In addition to non-uniformity of temperature, nearly all conventional forge furnaces suffer from flame impingement. Both these factors make it very difficult to apply pyrometric control to such furnaces, the main difficulty being that the location of the pyrometer should be such that the temperature indicated or recorded by it is not exceeded by that of any other part of the furnace. Again, it is only in very recent years that instruments have been available which are capable of indicating, recording, and controlling forge-furnace temperatures and at the same time can withstand forge conditions. Temperatures of 1200–1400° C. are a little beyond the capabilities of ordinary thermocouples for reliable continuous operation, and so far the optical pyrometer has not been made automatic even for indicating purposes, and requires human direction, focusing, and adjustment to obtain a reading. The radiation pyrometer remains, and here again it is only in recent years that this has been made sufficiently robust to withstand forge conditions. These remarks apply

to the application of pyrometric control to the furnaces, and even where this has been done successfully, it is advisable to check the temperature of the steel in the furnace. For the latter purpose, three main types of pyrometer have been used—the optical, the radiation, and the photoelectric. The radiation pyrometer as applied to individual spot-checks has always suffered from being too slow in action, and it requires care in use especially in regard to the attainment of blackbody conditions. However, a luminous flame does not affect the readings to any material extent. The photo-electric pyrometer, whilst being very accurate and capable of giving instantaneous readings, is at present too expensive for application to a forge furnace.

Optical pyrometers provide a very useful means of checking furnace or metal temperatures, but care should be taken to see that the temperatures observed are not affected by flame; when readings are being taken, the furnace should be momentarily turned down if this is possible. It is not always practicable to sight the optical pyrometer on the charge in the furnace, and often the temperature of the steel is measured after withdrawal from the furnace; it is usually most satisfactory to measure the temperature after the first hammer blow has caused the heating scale to fall away. Naturally, a temperature somewhat below that prevailing when the charge left the furnace is to be expected under such conditions, and due allowance must be made for this when assessing the furnace temperature from such readings.

The estimation of furnace temperatures by eye and experience is a useful aid to the avoidance of overheating when used together with some form of pyrometer. An observation of furnace conditions will often indicate whether a furnace or charge is being uniformly heated or not. Not the least important factor in avoiding overheating is the need for skilled furnacemen who are really interested in their job. The orderly charging and discharging of batch-type furnaces so that each piece of steel receives the same amount of heating is necessarily dependent on the human element, and in this respect continuous reheating furnaces have much to commend them. Such furnaces usually lend themselves more readily to automatic temperature control; care should be exercised, however, to ensure that the steel is not allowed to remain in the furnace for too long a time in the high-temperature zone; this may occur if a hammer breaks down or if continuous operation of the furnace is interrupted.

Where drop-forgings are made " off the bar," the use of continuous furnaces is to a large extent precluded, and where such work is carried out with batch-type furnaces, care should be exercised to see that the " front ends " of the bars are not overheated. This can often occur because of the desire of the operator to " chain-stamp " several forgings from one heat if possible.

Although they are perhaps not applicable at present to all the various sections of steel and partly formed forgings now reheated for drop-forging, there is a distinct possibility that electrical heating methods such as resistance and induction, both of which can be accurately controlled, will provide the heating methods of the future for small sizes or special applications. By the use of such methods it should be possible to eliminate overheating entirely.

It has been found a difficult task to prescribe maximum forging temperatures for each class of steel. Even different heats of the same type of steel may well have a different susceptibility to overheating. Extrapolation from the solidus line of the equilibrium diagram is not practicable, since it appears that overheating occurs in varied degrees at temperatures well below the solidus. Generally, it may be stated that none of the alloy steels used in the aircraft industry should be allowed to exceed 1250° C. for any length of time; temperatures well below this will often allow of satisfactory forging on some parts if the steel has been heated throughout its mass. On the other hand, some types of forgings are difficult to forge, especially upset gears, rings, and flanges, where a large amount of metal displacement takes place, and reheating and restriking are often necessary to obtain the required shape. The last operation may entail only a small amount of work and hence such forgings may suffer from overheating; it is significant that forgings of these types were the cause of many complaints of overheating. In the same way, forgings which are restruck for dimensional or other defects are also liable to suffer from overheating. It is essential that the forging should receive as much work as possible in the final heat. Some experimental work on the effect of work on overheated steel showed that 30% reduction of area by forging from the same temperature was sufficient to refine the grain of the steel and prevent a coarse fracture from being obtained, but smaller amounts of work may need careful investigation.

The systematic routine detection of overheating in the product may also be used to control over heating. This can be carried out by the use of pilot bars or forgings, by examination of integral test-bars on large forgings, or by examination of a percentage of the forgings where small forgings are concerned. The fracture test is the most reliable one to use, but the results can always be correlated in important cases with a full metallurgical examination, involving surface examination, metallographic examination, and mechanical tests. All methods should be based on the control of each shift's production and, of course, on different casts of steel if more than one cast is used during a shift. Equipment such as that described under

the heading of the fracture examination should be available to deal quickly with representative samples of each shift's production, so that it is not cleared for heat-treatment or further costly processing unless a satisfactory negative reaction to overheating is obtained. Pilot test-pieces may be used which take the form of two or more bars or forgings placed at each end of the initial furnace charge and left there until the completion of the shift or production period, after which they are fabricated into forgings and checked for overheating. The deliberate subjection of steel to the extreme conditions prevailing during any particular production period and the destructive testing of such steel, should prevent any danger of overheated forgings escaping detection if the pilot test-pieces are satisfactory. This method necessitates the checking of each cast of steel for its susceptibility to overheating during the production period over which it will be used, and to determine that it does not overheat to an extent which prevents full recovery of the metal on being forged and heat-treated; and, although perhaps more elaborate than the method of destruction of a percentage of forgings by fracture testing, it is more economical, and if carefully controlled will ensure a satisfactory product. Whatever method of sampling is adopted, it must be representative, and fracture standards are very necessary. Experience has shown that systematic technical control of the heating process is necessary if overheating is to be avoided; by regular observation and supervision by experienced personnel it is possible to reduce both the incidence and severity of overheating in drop-forgings.

Reclamation of Overheated Steel.

With regard to the reclamation of overheated forgings, various special heat-treatments have been suggested and used with varying degrees of success. So far it has not been found possible to reclaim burnt steel or even severely overheated steel—*i.e.*, steel which shows oxide tints or films in the crystal facets when fractured. However, the less severe types of overheating, whilst not responding to normal heat-treatment methods, show a fair measure of response to special heat-treatments, and amongst those which have been used are :

(1) Repeated normalizing operations (perhaps as many as six times).

(2) Normalizing at temperatures of 50–100° C. higher than usual, followed by normalizing at the usual temperature.

(3) Soaking for a period of a few hours at case-hardening or higher temperatures (1150° C. has been used).

All these treatments are followed by the usual orthodox hardening and tempering operations.

In practice, these operations have proved difficult from two standpoints, namely, high costs, and the high degree of scaling and the loss of dimensions which take place at elevated temperatures. It has been found expedient, for instance, in the case of soaking for any period of time at elevated temperatures, to pack the forgings in sand in carburizing boxes with the lids luted on. Thus reclamation by heat-treatment is not always a practicable proposition, especially if the overheating has not been detected until after the forgings have been machined. Again, in adopting any of these special heat-treatments for overheated steel, the possibility of severe local overheating in parts of the forging which are not refined by the treatment should not be overlooked. Another factor which might govern such treatments is that repeated heat-treatment is not treated too kindly by the various aircraft-steel specifications. For instance, most of them make no mention at all of a normalizing treatment, except for case-hardening steels, but specifically state that the steel shall not be rehardened more than three times.

There is no doubt that a carburizing treatment has a beneficial influence on a slightly overheated steel, but a double normalizing treatment with the first operation carried out at 50° C. higher than usual is also especially useful in ensuring complete grain refinement in slightly overheated steels, and all important components such as connecting rods and crankshafts would benefit from this treatment. Experimental work on the effect of special heat-treatments on overheated steel showed that repeated normalizing was better than a single treatment at elevated temperatures.

One rather lengthy reclamation treatment for overheated alloy steel, which has been used in the U.S.A., consists of soaking for 8 hr. at 2250° F. (1232° C.) and cooling, followed by soaking for 8 hr. at 2000° F. (1093° C.) and cooling, followed by soaking for 8 hr. at 1750° F. (955° C.) and cooling, and finally by the usual hardening and tempering treatment. This treatment was tried out on some overheated S.A.E. *X*4340 ($1\frac{3}{4}$% nickel–chromium–molybdenum) steel with successful results as far as elimination of the overheated state was concerned. The appearance of specimens subjected to transverse fracture tests before and after the reclamation treatment is shown in Figs. 21 and 22 respectively. They reveal an overheated granular fracture before treatment and a satisfactory fibrous fracture after treatment. Metallographic examination of specimens of the steel before and after the special treatment showed a positive and a negative reaction respectively to the dark " grain-boundary indications " produced by the 10% sulphuric-acid/ 10% nitric-acid reagent, thus confirming the fracture-test results. Such a treatment is, of course, very costly, and would be practicable only if the forgings or parts were protected from the

atmosphere during heating. In the case of the steel mentioned above, the samples were not so protected and considerable scaling took place, reducing the $1\frac{1}{2}$-in. dia. bar to $1\frac{3}{8}$ in. after treatment.

Overheating in the U.S.A.

Some time ago the author visited the United States, and a few remarks on overheating in drop-forgings as experienced in that country may be added in conclusion. An epidemic of overheating, or "grain-coarsening" as it is termed there, occurred as it did in Britain when the production of drop-forgings was accelerated and the demands in service of many vital aircraft components were increased. For the detection of overheating, fracture testing has been generally adopted, and attempts have been made to standardize fractures and correlate them with mechanical properties, including fatigue strength. Pickling and surface examination are not looked upon favourably, and are considered by some leading drop-forgers as too unreliable. Concerning the fracture test, one interesting feature of American steels is that when overheated, only part of the fracture usually shows mat crystalline facets in a very spasmodic degree. The reason for this is obscure, but it seems peculiar to American steels, and there is a possibility that steels well treated with aluminium to control inherent grain-size are more generally resistant to grain-coarsening.

In the case of large drop-forgings for major components, such as propeller shafts, crankshafts, master rods, airscrew spiders, &c., the fracture test has been largely adopted as a substitute for tensile testing. Whilst it is not proposed to discuss here the relative merits of the British and the American systems of inspecting and testing such components, it may be said that the procedure adopted in America resulted in an important saving in alloy steel, since the fracture test, when properly conducted, could be and was carried out on major parts on test-prolongations as small as, say, 3 in. long by 1 in. sq.; whereas tensile testing on each part demanded a much larger test-piece, which often had to be of consistent ruling section with the forging. The practice of carrying out nicked-fracture tests on integral test-bars for major aircraft components in steel is, of course, not new, and is an essential part of the British Standard aircraft specifications for such components. In some cases nicked-fracture tests must be conducted on both ends of the forging. However, such tests must be accompanied by tensile and impact tests, which necessitate that the diameter of the test-bar shall be equivalent to the ruling section of the forging. In the United States, larger production, larger casts of alloy steel, the use of continuous heat-treatment furnaces, and automatically controlled quenching procedures have made it possible to relax tensile testing to some extent and to control heat-treatment by hardness and fracture testing, reducing tensile testing to perhaps one in 500 forgings or even one per cast. On deep-hardening steels this procedure combined with careful acceptance-testing has saved a good deal of material, facilitated production, and at the same time ensured freedom from serious overheating of each forging. Unsatisfactory or doubtful fractures were disposed of by tensile testing where the test-coupon permitted or, alternatively, by tensile tests on a percentage of components in cases where the fracture test has been previously well correlated with the physical properties. On case-hardening steels or on steels which are not fully heat-treated until after machining, the fracture test has been employed, so that overheated forgings have been eliminated before expensive machining operations have been carried out. In such forgings as, for example, propeller shafts and crankshafts, where a small test-coupon was not practicable from a forge point of view, a saving in alloy steel used for testing has been achieved by two methods. In some cases a test-slice $\frac{1}{2}$ in. thick has been cut from the end of the forging, heat-treated apart from the forging, and longitudinal fractures carried out, experience having shown that the acceptable standard is that which shows complete absence of facets in the longitudinal fracture. In other cases the same $\frac{1}{2}$-in. test-slice has been nearly parted-off by sawing, leaving a segment large enough for satisfactory examination; this was then locally flame-hardened, tempered, and fractured by using a wedge in the saw-cut, thus giving a transverse fracture which is more sensitive to overheating. This second practice avoided serial numbering.

Thus the fracture test for the detection of overheating has also been used to check the quality of the heat-treatment, and there is no doubt whatever that a considerable saving in material and man-hours has been effected. On the other hand, not much attention has been paid to parts which are not large enough to carry an integral test-bar, but which may be very important and which may also become overheated. However, a good deal of progress has been made in the direction of preventing overheating, especially by the use of continuous rotary furnaces, reliable automatic temperature control, and the use of rather low maximum forging temperatures, combined with larger and more powerful hammers which facilitate production of many forgings without reheating.

Conclusion.

There is known to be a wide divergence of opinion regarding the degree of overheating in alloy steels which is detrimental to their serviceability and

in the present paper an attempt has been made to present various aspects of the subject. Although the urgent need for using alloy-steel drop-forgings in " borderline " overheated conditions has passed with the war, the history of what was a serious problem should not be allowed to pass unrecorded.

Alloy-steel forgings have a prominent place in aeronautical power-units, where quality must be second to none, and for this reason the whole subject of overheating and burning merits further research. Some aspects of the subject which are still obscure may be mentioned in conclusion. The susceptibility to overheating of steels of various compositions and made by different processes needs investigation primarily from the point of view of the relationship between the temperature and time needed to produce serious damage, or rather, to avoid it. The effect of different furnace atmospheres and the possible effects on overheating of the different types of scales which they produce should further illuminate the subject. Another important aspect is the effect of hot work on overheated steel, particularly of small amounts of work such as would effect less than approximately 30% reduction of area. There is also a possibility that steels having different grain-growth characteristics at forging temperatures will vary in susceptibility to overheating. The behaviour of steels heated to forging temperatures by electric-resistance and induction methods would form an interesting comparison with those heated in the orthodox furnaces of to-day. Perhaps important, too, from an economic point of view, is an investigation of the success to be obtained with methods of reclaiming steel overheated to various degrees. For detecting overheating, a non-destructive and more precise method of estimating the degree of damage suffered by the steel would be welcomed by drop-forgers, as would more authentic evidence on the loss of fatigue strength. At the moment, the destructive fracture test is pre-eminent, but even this needs to be standardized throughout the industry. Metallographically, the detection of overheating in alloy steels should not be without hope and will possibly proceed by the use of electrolytic polishing and the discovery of new etching reagents which are more suited to the almost submicroscopic nature of the defect than the present reagents used. Considering the high value, both monetary and otherwise, of many alloy-steel drop-forgings, it may well be concluded that research is needed to illuminate the still somewhat obscure phenomenon of overheating.

Acknowledgments.

The author wishes to express his thanks to the Directors of Smethwick Drop Forgings, Ltd., Kidderminster, for permission to publish the results of certain work carried out whilst he was in their service, and also to Mr. H. A. Whiteley, of Kidderminster, whose interest and encouragement in the early stages were invaluable.

REFERENCES.

1. A. Preece, A. Hartley, S. E. Mayer, and J. Nutting: *Journal of The Iron and Steel Institute*, 1946, No. I., p. 237 P.
2. G. W. Austin: *The Iron and Steel Institute*, 1936, *Special Report No.* 14, p. 189.
3. A. Stansfield: *Journal of The Iron and Steel Institute*, 1903, No. II., p. 433.
4. H. M. Howe: " The Metallography of Steel and Cast Iron," pp. 141, 202, and 490. London, 1916: The McGraw-Hill Book Co., Inc.
5. A. Sauveur: " The Metallography and Heat-Treatment of Iron and Steel," p. 259. Cambridge, Mass., 1916: The McGraw-Hill Book Co., Inc.
6. F. Osmond and J. E. Stead: " The Microscopic Analysis of Metals," pp. 145, 243. London, 1913: Chas. Griffin and Co., Ltd.
7. G. Tammann: *Zeitschrift für Metallkunde*, 1930, vol. 22, p. 224; " Lehrbuch der Metallkunde," pp. 10–12. Leipzig, 1932: Leopold Voss.
8. E. Houdremont: " Einführung in die Sonderstahlkunde," pp. 51, 276–278. Berlin, 1935: Julius Springer.
9. W. E. Jominy: *Transactions of the American Society for Steel Treating*, 1929, vol. 16, p. 298.

[This paper was discussed jointly with the following four by A. Preece, A. Hartley, S. E. Mayer, and J. Nutting on " The Overheating and Burning of Steel," by W. E. Goodrich on " Overheating and Burning of Nickel–Chromium–Molybdenum Steel," by F. C. Thompson and L. R. Stanton on " The Effect of Oxygen on the Isothermal Transformations of Steel, and a Suggested Test for Burning," and by J. Woolman and H. W. Kirkby on " Some Experiments on Overheating."]

THE OVERHEATING AND BURNING OF STEEL.*

By A. PREECE, M.Sc., A. HARTLEY, B.Sc., S. E. MAYER, Ph.D., and J. NUTTING, B.Sc.
(Leeds University).

Paper No. 18/1946 *of the Alloy Steels Research Committee.*

(Figs. 10 to 35 = Plates XIII. to XV.)

Synopsis.

The overheating properties of a wide variety of steels have been examined. The temperatures of overheating have been determined on the basis of the fracture and etch tests, a critical examination of these tests showing them to be satisfactory for this purpose.

There would appear to be no clear relationship between the overheating temperature and the normal specified analysis of the steel, or its oxygen and nitrogen contents. Open-hearth steels have generally a higher overheating temperature than electric steels. An unexpected correlation has been observed between the inclusion content of a steel and its overheating temperature.

Furnace conditions, such as composition of the atmosphere, soaking time, and the rate of cooling, have been studied in relation to overheating. From this, the possibility of a slow-cooling treatment as an effective method of restoring overheated steels has been indicated. The effect of overheating upon the tensile and Izod properties has also been examined.

Results obtained in this investigation provide further information on the mechanism of overheating.

PART I.—Introduction.

By A. PREECE, M.Sc.

It is well known that in the heating of steels for forging and hot working generally, excessive temperatures produce weak structures which may be temporary or permanent in character. In the first place, there is the normal development of a coarse grain-size. With steel this does not present much difficulty, since it is generally broken down by deformation during hot working, and, where this is inadequate, further refinement may be brought about by heat-treatment. At higher temperatures, however, weak structures of a permanent nature are developed. A clearly defined example of this is found in steel in which incipient fusion of the grain boundaries has occurred. This condition is easily recognized in practice, as the fracture has a characteristic granular appearance and the microstructure shows voids and oxide films around individual grains. Such a steel is described as "burnt." It has very poor forging properties and a low tensile strength.

A granular fracture alone, however, cannot be taken as evidence of burning, since similar fractures can be obtained after heating to temperatures well below those required for true burning. In this lower range, the fracture varies from granular to a type containing a number of mat crystal facets on a fibrous background. Steels in which these structures have been developed as a result of heating to this lower range of temperature are described as "overheated" to distinguish them from burnt steels in which incipient fusion or crystal separation has occurred.

A general similarity between these structures has led to the impression being gained that the difference between overheated and burnt steel is one of degree only. This is clearly reflected in the theories put forward to explain these weak structures, especially where evidence of incipient fusion could not be found or where it was known that the temperatures used were too low for it to occur. The following may be quoted as typical:

(*a*) Fusion of non-metallic constituents which were then assumed to force the crystals of austenite apart, enveloping them with a thin oxide film.

(*b*) Crystal separation by the release of gases.

(*c*) Preferential oxidation of chromium, aluminium, &c., producing an oxide film between the crystals.

While each of the foregoing phenomena could result in a form of intergranular weakness,

* Received January 14, 1946. This paper is published by authority of the Alloy Steels Research Committee. The views expressed in it are the authors' and are not necessarily endorsed by the Committee as a body.

evidence obtained in the present investigation and described in the following section, has shown that they play no part in producing the granular or faceted structures found in overheated (as distinct from burnt) steels.

The fact that, in both overheated and burnt steels, suitable etchants will develop a crystal structure which corresponds to the grains in the fracture, also encouraged the belief that overheating was merely an initial stage of burning. Furthermore, since a granular or faceted fracture denotes some form of intergranular weakness, fracture and etch tests have become a routine method of examination for freedom from these ill effects of excessive temperatures. Where the tests are positive the steel is suspected and is usually discarded. It would seem from results obtained in the present investigation that this method of testing is too severe, since it can be shown that these structures may be developed to an appreciable extent before mechanical properties are materially affected. The difficulty lies in the absence of some means of indicating the stage in the development of these structures where the mechanical properties of the steel are seriously impaired.

Industrially, the problem is further complicated by the wide variation in overheating tendencies of consecutive casts of steel, even when precautions are taken to keep steelmaking conditions as constant as possible. It is thus impossible to predict a safe working temperature for any steel from a knowledge of the cast history and the usual analysis. Furthermore, as overheating does not seriously impair the hot-working properties of steel, no evidence of this defect is given during forging. It will be clear, therefore, that the true assessment of these granular or faceted structures has become a major problem in the forging and allied industries.

In earlier investigations no serious attempt was made to distinguish clearly between overheating and burning, and, as attention was mainly directed to the higher temperature ranges, the results refer to the burning propensity of the steel.

Among the more important researches may be mentioned the pioneer work of Stansfield [1] and of Stead,[2] who experimented in the region of the solidus. Later work by Jominy [3] was also concerned with this higher temperature range. More recently a valuable contribution to our knowledge of the subject has been made by Austin,[4] who showed that the low strength of certain steels was associated with the appearance of mat granular structures in the fracture. He also showed that the grains revealed in the fracture could be outlined by a suitable etching technique.

A very comprehensive survey of the literature, which may be recommended to readers, has been published by The Iron and Steel Institute.[5]

The general impression obtained from published work is that a number of factors are involved in the formation of the weak granular structures, but little is known concerning their relative importance or the mechanism involved. Many of the conclusions put forward are the result of industrial experience, rather than of a systematic examination in which each controlling factor has been separately studied.

The present investigation was undertaken to examine, in the first place, the relative importance of variables such as temperature, furnace atmosphere, heating and cooling rates, &c., on overheating properties. The results of such a survey would be of practical use, and at the same time would serve as an approach to the more fundamental problem of elucidating the mechanism of overheating.

As a first step it was thought advisable to determine the overheating temperatures of a large number of steels made by different processes. The most satisfactory means of identifying the earliest stages of overheating were found to be the fracture and etch tests, provided that the steel was suitably heat-treated before testing. As indicated in the following section, this heat-treatment is most important.

Since embrittlement is commonly held to be one of the most serious consequences of overheating, Izod tests were carried out on the steels in addition to the fracture and etch tests.

It was clear that the earlier part of this investigation would be simplified by avoiding temperatures near the solidus, where incipient fusion of the grain boundaries would mask the overheating effects. By choosing steels of moderately low carbon content, overheating could be produced at temperatures well below the solidus. As the work proceeds, the higher-carbon steels will also be included.

The results of the survey have proved to be informative. They have shown the relative importance of furnace conditions and have brought out some interesting features connected with the composition of the steel. Neither the elements normally specified, such as carbon, sulphur, phosphorus, silicon, nickel, chromium, &c., nor the residuals, seem to be important. The gas content of the steels has received attention, but the results are not conclusive.

In addition, the correlation between the incipient overheating temperature and the general physico-chemical properties of steels is being studied.

The correlation of the incipient overheating temperature with the inclusion count has given unexpected results. They both increase together, suggesting that the inclusions may have a direct

effect on overheating, or that conditions which give rise to dirty steel also promote a high resistance to overheating. Though contrary to popular view, this conclusion would appear to be supported by the fact that of the steels examined in this investigation, electric steels have, in general, a lower overheating temperature than corresponding open-hearth steels.

Information has also been obtained concerning the mechanism of overheating, though further work is necessary for a complete explanation. It has been found that the changes in the austenite grains which are responsible for the overheating, are diffusion processes, and that they operate while the steel is cooling through the overheating range to the incipient overheating temperature. Extreme rates of cooling over this limited range, such as quenching or furnace cooling, considerably minimize, or even completely suppress, the overheating effect. Application of the slow-cooling treatment to overheated steels has given promising results as a most effective method of resuscitation.

The investigation is being continued.

PART II.—The Overheating Properties of Steels.

By A. PREECE, M.Sc., A. HARTLEY, B.Sc., S. E. MAYER, Ph.D., and J. NUTTING, B.Sc.

Experimental.

(a) *Furnace Equipment.*

The first requirement was a high-temperature furnace, in which steel specimens, 8 in. long, could be heated under accurately known conditions of time, temperature, and furnace atmosphere.

A gas-fired muffle furnace, heated by four tangential nozzle-fired burners, was chosen. Each burner could be adjusted individually to obtain an adequate zone of constant temperature under different conditions of heating.

The temperature was automatically controlled by means of magnetic valves in both gas and air mains; these valves were operated by thermocouples placed in the muffle compartment which consisted of a sillimanite tube of 4 in. internal dia. and 4 ft. long. The arrangement is shown in Fig. 1. The steel specimens were supported on an alumina block with one thermocouple alongside and a second couple underneath the block. The temperature was controlled by the lower thermocouple while the muffle tube was being charged and until the temperature of the steel specimens approached that of the furnace. During the soaking period the temperature was controlled by the thermocouple alongside the steel bars. By careful adjustment of the by-pass and magnetic valves, the temperature inside the muffle could be maintained well within ± 10° C. A zone, 9 in. in length, over which the temperature varied by only 5° C. ensured even heating of the specimens. The controlled atmosphere in which the specimens were heated entered at one end of the tube and was brought up to temperature on passing through a heat interchanger; this consisted of a ring of narrow-bore tubes built around a hollow cylinder closed at both ends. The gases then passed over the specimens and through holes in two baffle blocks, finally escaping through a small chimney at the end of the muffle tube.

It was evident that furnace atmospheres could not be produced by burning town's gas and air at the inlet end of the muffle tube, since this would seriously upset the temperature distribution and damage the tube by excessive heating at this end. The controlled-atmosphere unit shown in Fig. 1 was therefore constructed.

Town's gas was burnt on a grid at the bottom of the combustion chamber; the amounts of both gas and air were carefully measured by meters. A Meker grid, 1½ in. in dia., and a combustion chamber, 5 in. in dia., enabled a steady flame to be maintained on the grid with a low air/gas ratio, and gave as combustion products a mixture of gases containing a high carbon monoxide and hydrogen content, but no unburnt hydrocarbons. One such sample had the following analysis:

N_2.	CO_2.	CO.	H_2.	H_2O.
55·7%	3·6%	10·8%	12·2%	17·7%

The composition of this mixture remained within narrow limits during a run.

The gas was then passed through a direct cooling condenser filled with Lessing rings, which brought the moisture content down to about 2%. From the condenser the gas was led to the inlet end of a blower, where a predetermined quantity of secondary air was admitted. Combustion was completed at the entrance of the muffle tube, where the relatively small amount of heat developed could be easily accommodated by adjusting the burners.

After this further reaction at the entrance to the muffle tube, the products of combustion, containing approximately 12% of CO_2, 10% of H_2O, and 78% of N_2, resembled fairly closely the products of complete combustion of producer gas.

By suitably adjusting the amount of secondary air, an atmosphere could be obtained containing (*a*) carbon monoxide, representing incompletely burnt fuel, or (*b*) free oxygen, to represent conditions obtained by the use of excess air for combustion. Arrangements were also made to add known quantities of sulphur dioxide to the gas immediately before it entered the muffle tube, so that the effect of sulphur in the furnace atmosphere could be examined.

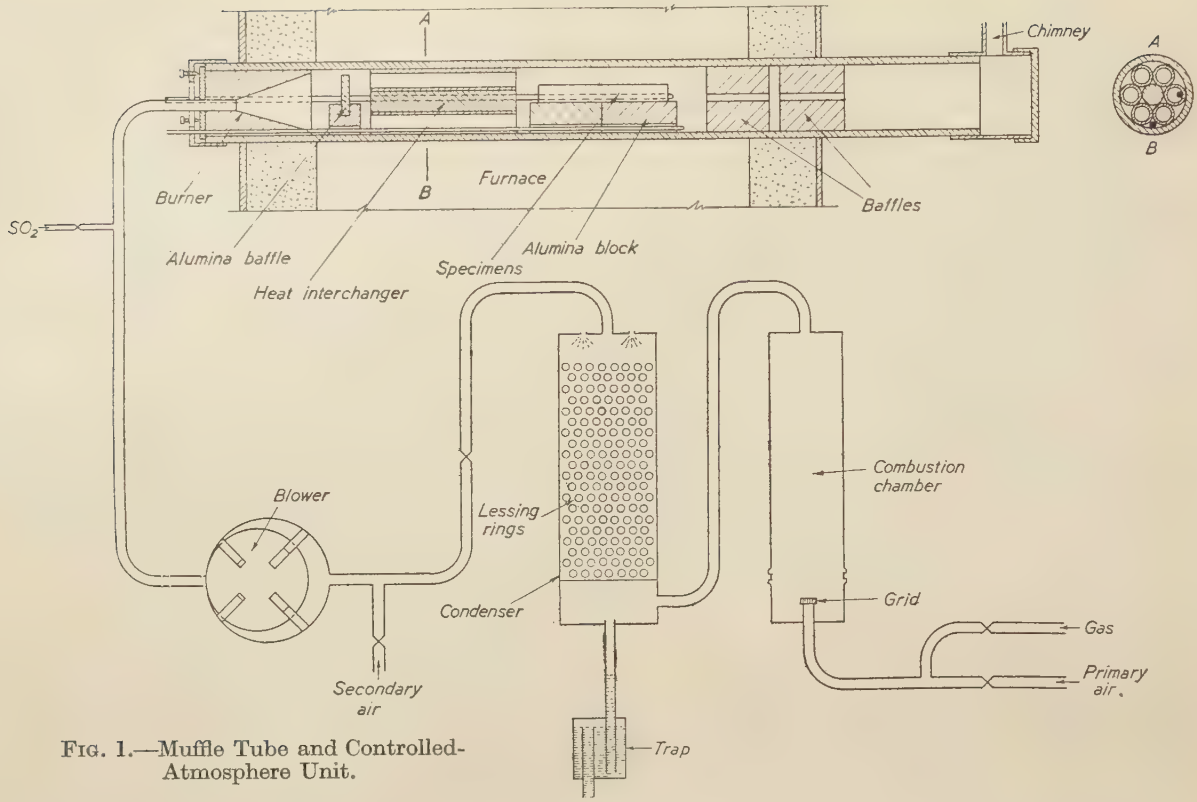


FIG. 1.—Muffle Tube and Controlled-Atmosphere Unit.

Two steel bars, each 1 in. in dia. and 8 in. long, could both be heated in the furnace at the same time. For temperatures above 1325° C., a layer of alumina grog was placed on the specimen block to absorb molten oxide. Specimens were heated to temperature in a little more than 30 min. and were soaked for a further 30 min.

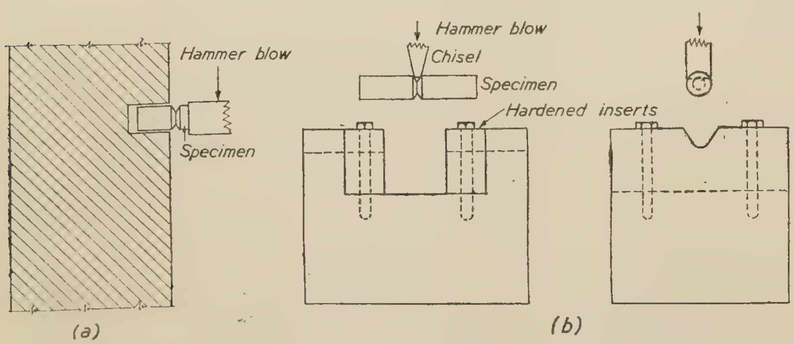


FIG. 2.—Methods Used for Fracturing the Specimens.

A small platinum-wound tube furnace and a Silit-rod furnace were also used for dealing with small specimens.

In the subsequent heat-treatment, heating for oil-quenching was carried out in a large gas-fired muffle furnace, and an electrically heated lead bath was used for tempering. Accurate temperature control was most essential in the tempering operation, as slight differences in tempering temperature, especially in the region of 600° C., cause a wide variation in the impact value.

(b) *Fracture Test.*

The fracture test, because of its obvious importance, was standardized. Preliminary trials showed that deformation during fracture tended to mask the structure, and consequently an impact method of breaking notched specimens was employed.

Where it was necessary to fracture a short length from the end of a bar, the end was turned down to $\frac{3}{4}$ in. dia., notched, and inserted in a hole in a heavy steel pillar, as shown in Fig. 2(*a*). The specimen was then fractured at the notch by striking the protruding part with a heavy hammer.

For specimens that were too short to be fractured in this manner, or in cases where it was desired to break the specimen at the centre, the steel bar was placed on the V-block shown in Fig. 2(*b*). A blunt chisel held in the notch, as shown, was then struck a heavy blow. No appreciable deformation occurred as long as precautions were taken to ensure sharp notches. The first specimens were notched on opposite sides only, so that, apart from the notched portion, the fractured surface contained the whole of the cross-section. As no difference in the appearance of the fracture was found from centre to edge, subsequent specimens were notched all

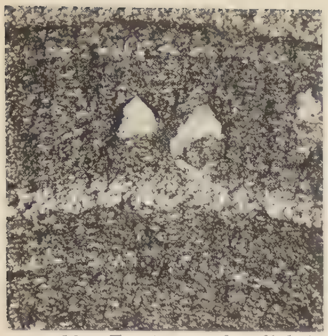


FIG. 10.—Fracture of slightly overheated steel, showing facets. × 10.

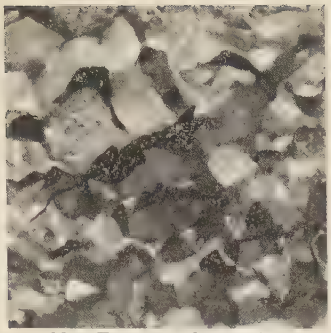


FIG. 11.—Fracture of severely overheated steel, showing coarse granular fracture. × 10.

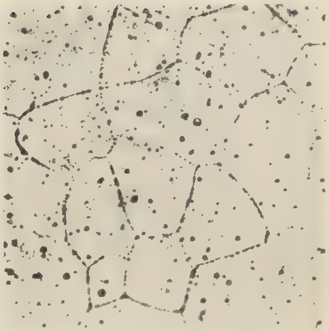


FIG. 12.—Overheated steel etched with 10% H_2SO_4 and 10% HNO_3 (nitro-sulphuric etchant) and repolished. × 75.

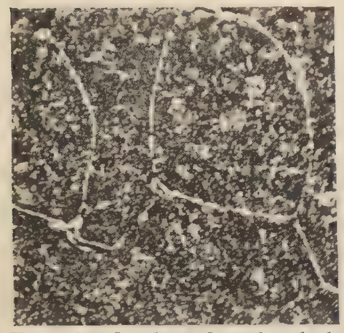


FIG. 13.—Overheated steel etched with ammonium persulphate. × 75.

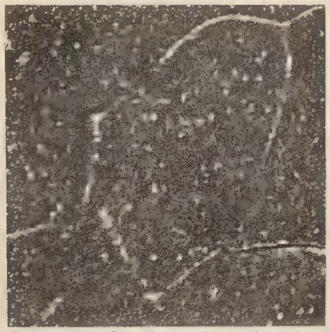


FIG. 14.—Overheated steel etched with molten zinc chloride. × 75.

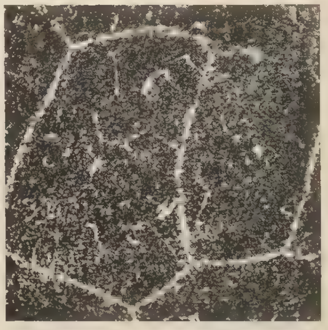


FIG. 15.—Overheated steel etched with ammonium nitrate. × 75.

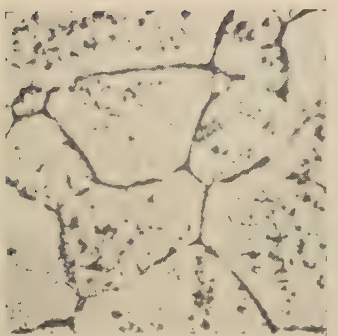


FIG. 16.—Steel seriously embrittled by overheating. Etched with ammonium nitrate. × 40.

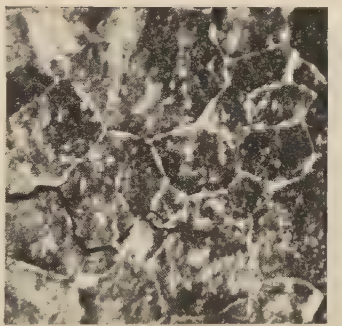


FIG. 17.—Fracture following grain boundaries. Etched with ammonium nitrate. × 20.

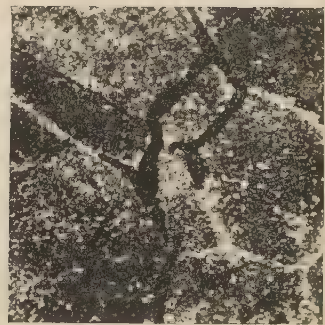


FIG. 18.—As Fig. 17. × 75.

(Micrographs reduced to four-fifths linear in reproduction.)

[*Preece and others.*

[*To face p.* 240 P.

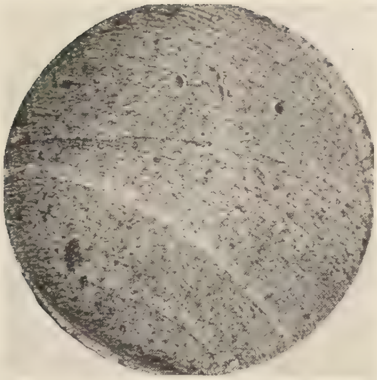


FIG. 19.—Fracture of steel No. 79 in the as-rolled condition. × 4.

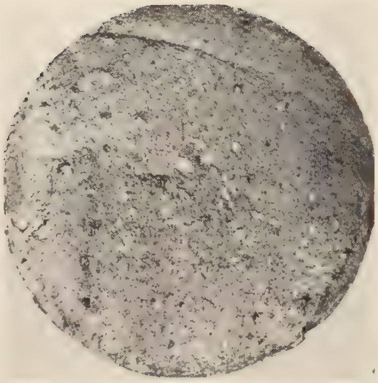


FIG. 20.—Fracture of steel No. 79, heated at 1250° C. for 30 min., air-cooled, and heat-treated. × 4.

FIG. 21.—Fracture of steel No. 79, heated at 1275° C. for 30 min., air-cooled, and heat-treated. × 4.

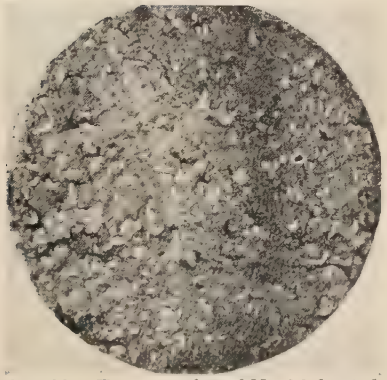


FIG. 22.—Fracture of steel No. 79, heated at 1300° C. for 30 min., air-cooled, and heat-treated. × 4.

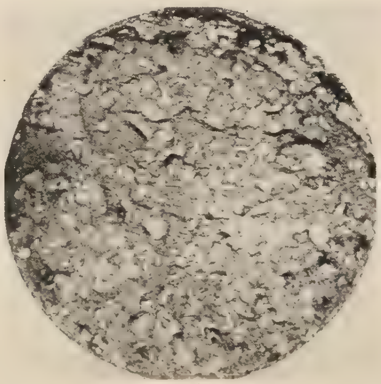


FIG. 23.—Fracture of steel No. 79, heated at 1325° C. for 30 min., air-cooled, and heat-treated. × 4.

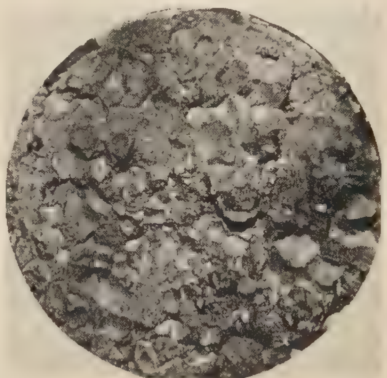


FIG. 24.—Fracture of steel No. 79, heated at 1350° C. for 30 min., air-cooled, and heat-treated. × 4.

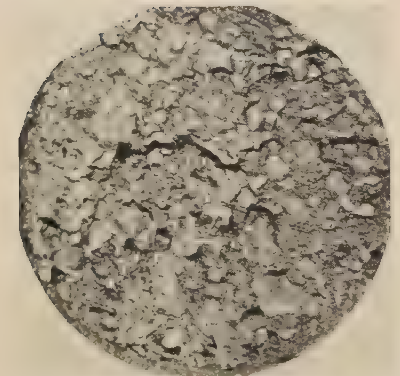


FIG. 25.—Fracture of steel No. 79, heated at 1375° C. for 30 min., air-cooled, and heat-treated. × 4.

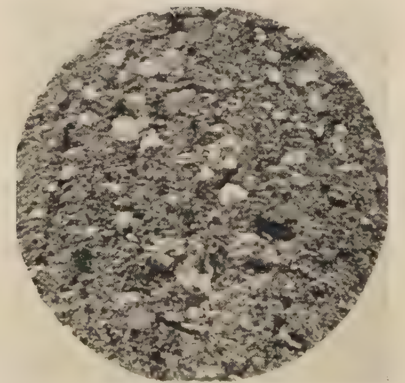


FIG. 26.—Fracture of steel No. 54, heated at 1350° C. for 5 min., air-cooled, and heat-treated. × 4.

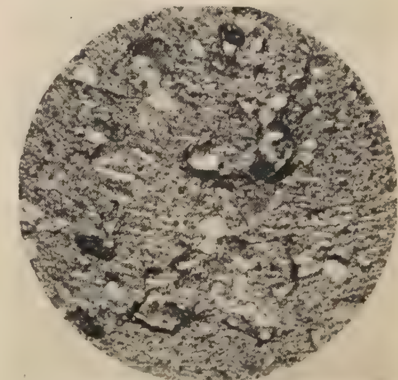


FIG. 27.—Fracture of steel No. 54, heated at 1350° C. for 20 min., air-cooled, and heat-treated. × 4.

[*Preece and others.*

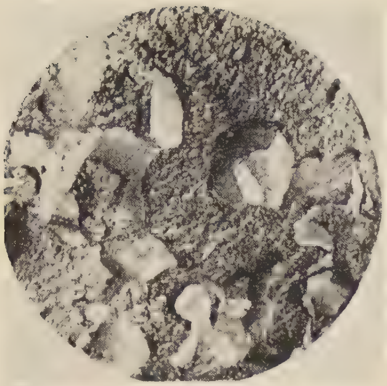


FIG. 28.—Fracture of steel No. 54, heated at 1350° C. for 1½ hr., air-cooled, and heat-treated. × 4.

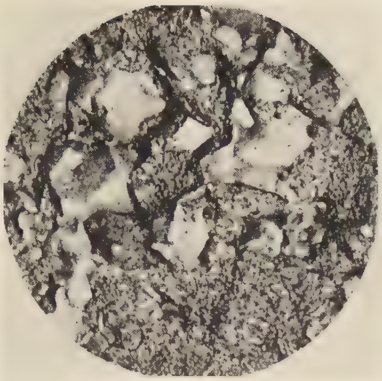


FIG. 29.—Fracture of steel No. 54, heated at 1350° C. for 5½ hr., air-cooled, and heat-treated. × 4.

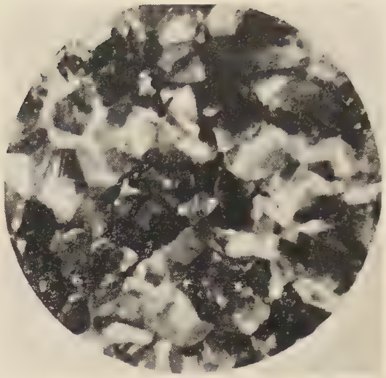


FIG. 30.—Fracture of steel No. 54, heated at 1375° C. for 30 min., water-quenched. × 4.

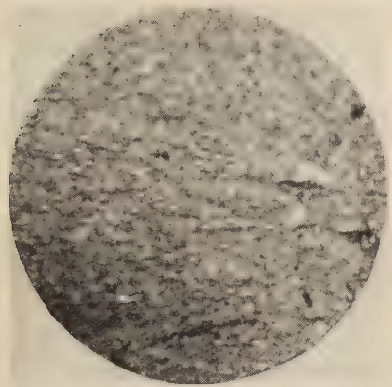


FIG. 31.—Fracture of steel No. 54, heated at 1375° C. for 30 min., water-quenched, and heat-treated. × 4.

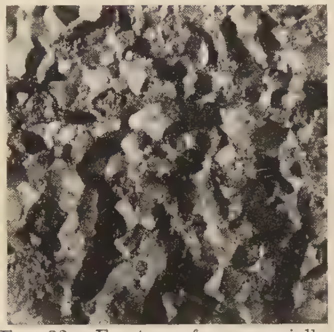


FIG. 32.—Fracture of commercially overheated steel, as received. × 4.

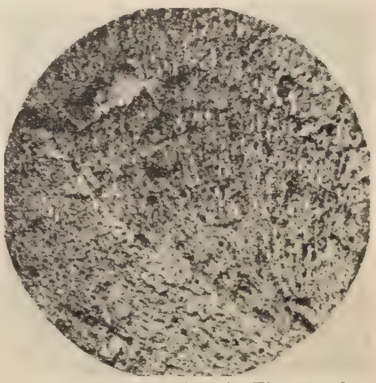


FIG. 33.—Same steel as in Fig. 32, after slow cooling from 1375° to 1200° C. and heat-treating. × 4.

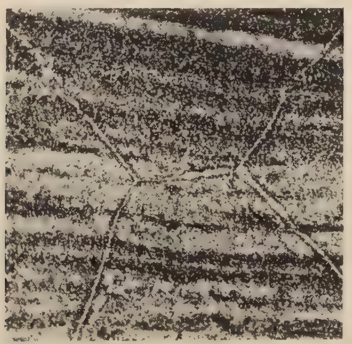


FIG. 34.—Overheated steel, showing flow lines and boundaries. Etched with ammonium nitrate. × 40.

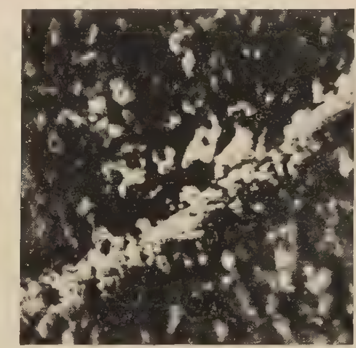


FIG. 35.—Overheated steel, showing boundary, etched with molten zinc chloride. × 380.

(Figs. 32, 34, and 35 reduced to four-fifths linear in reproduction.)

[*Preece and others.*

round, since this caused less tendency for deformation during fracture. Typical fractures of overheated steels are shown in Figs. 10 and 11.

(c) *Etch Test.*

Although a number of reagents have been suggested for developing the polygonal boundaries associated with overheating, they have not been found entirely satisfactory. In the first place, they reveal a macrostructure rather than a true microstructure. Secondly, those recommended as suitable for detecting the early stages of overheating are so violent that they have a tendency to develop etch-pits which mask the boundaries.

The nitro-sulphuric * etchant is the most efficient reagent for detecting the initial stages of overheating; an example of the etch is shown in Fig. 12. A complete account of the method of applying this reagent, together with photomicrographs, has already been given by Austin.[4] This etchant operates by preferential solution of that region of the metal which corresponds to the grain boundaries seen in the fracture. In one respect this action is unfortunate, since it removes from the etched surface those parts which have been changed in some way by overheating and which are therefore those regions calling for the most careful examination.

Of the other reagents, ammonium persulphate and nitric acid leave the boundaries as light-coloured ridges (Fig. 13). They are not effective unless overheating is well advanced.

In the present investigation a search was made for a more satisfactory etchant, *i.e.*, one that would show the true microstructure of the steel and at the same time reveal the change in the metal which gives rise to the weakened grain boundaries. It is these weakened grain boundaries that characterize overheating. Well over a hundred reagents, including molten salts, have been examined so far, but with little success. An example of an overheated steel etched with molten zinc chloride is given in Fig. 14. No reagent more efficient than the nitro-sulphuric etch has been found for indicating the incipient stages of overheating.

An ammonium nitrate electrolytic etch has given some interesting results. It is almost as efficient as the nitro-sulphuric etch for revealing incipient overheating, provided that the steel is in the fully heat-treated condition, *i.e.*, oil-quenched and tempered to maximum toughness. From the limited number of tests which have been carried out, it would appear that there is a complete reversal in the action of this etchant when the overheating becomes very severe. Until this severe stage is reached the microstructure shows white polygonal boundaries on a dark background (Fig. 15), but in three specimens, where the Izod value had been reduced by overheating to 10–20% of its normal value, the microstructure was as shown in Fig. 16, *viz.*, black boundaries on a white background.

As the investigation proceeds to the higher temperatures, and more specimens of severely overheated steel become available, it is hoped to examine further this interesting feature.

Details are given below of the three etchants which were found to be most useful in the present work.

(1) *Nitro-Sulphuric Etchant.*—An aqueous solution of 10% sulphuric acid and 10% nitric acid. The specimen should be immersed for 30 sec. and then swabbed with cotton-wool in running water. This operation is repeated three times, and the specimen is lightly repolished before examination.

(2) *Electrolytic Ammonium Nitrate Etchant.*—The specimen is made the anode in a saturated aqueous solution of ammonium nitrate. The etching time varies up to 3 min., with a current density of about 0·1 amp./sq.cm. at 6 V., the distance between the anode and the cathode being 2 cm. Platinum or stainless steel may be used as the cathode. The specimen does not require repolishing after etching.

The same solution can be used a number of times, since the ferric hydroxide precipitated does not interfere with the etching reaction. The *p*H value of the solution increases during use from 4·3 to 7, as is shown in Fig. 3. After

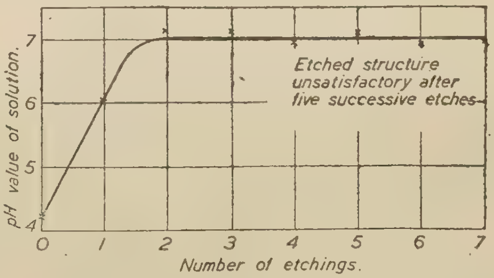


Fig. 3.—Variation of *p*H Value of Ammonium Nitrate Solution with Repeated Etching. Each etch of 2 min. duration at 6 V. and 1000 m.amp.; volume of solution : 55 c.c.; surface area of specimen : 8·5 sq. cm.

a number of successive etchings the clarity of the structure deteriorates.

(3) *Nitric–Picric Etchant.*—The usual mixture contains equal quantities of $2\frac{1}{2}$% nitric acid and 5% picric acid in alcohol.

The steels used in the present investigation are given in Table I.

* This etchant was developed by Slagg and De Belin at the Research Laboratories of Messrs Cammell Laird & Co., Ltd., in 1927.

Table I.—*Composition and Incipient Overheating Temperature of Steels Used in the Present Investigations.*

Sample No.	En Specification.	Analysis, %.										Method of Manufacture.	Not Overheated, ° C.	Incipient Overheating Temp., ° C.
		C.	Si.	Mn.	S.	P.	Ni.	Cr.	Mo.	V.	Pb.			
71	1A	0·13	trace	1·02	0·226	0·056	...	...	...	...	...	O.H.	1400	...
70	2A	0·11	0·121	0·45	0·034	0·019	...	...	...	...	...	O.H.	1400	...
77	3	0·18	0·26	0·68	0·027	0·032	0·28	0·18	...	...	...	E	1375	1400
32	3	0·13	0·26	0·59	0·029	0·020	...	...	...	...	...	O.H.	1400	burnt 1425 approx.
81	3	0·13	0·27	0·56	0·009	0·015	0·24	0·16	...	...	...	E	...	<1350
33	16	0·38	0·30	1·55	0·029	0·030	...	...	0·27	...	...	O.H.	1400	burnt 1425 approx.
21	16	0·30	0·30	1·44	0·010	0·031	...	...	0·36	...	...	E	1300	1350
23	18	0·38	0·25	0·73	0·019	0·016	...	1·00	...	...	...	E	1300	1350
13	21	0·32	0·27	0·71	0·044	0·029	3·16	...	...	...	...	O.H.	1350	...
41	22	0·39	0·24	0·64	0·010	0·012	3·68	0·30	...	...	...	E	1250	1300
61	22	0·40	0·21	0·63	0·012	0·010	3·63	0·28	...	...	...	E	1300	<1375
63	22	0·39	0·18	0·67	0·036	0·030	3·40	0·21	...	...	...	O.H.	1300	1325
78	22	0·36	0·13	0·60	0·014	0·011	3·54	0·19	...	...	...	E	1250	1275
34	24	0·40	0·21	0·56	0·021	0·031	1·46	1·54	0·25	...	...	E	1275	1300
42	24	0·38	0·30	0·60	0·014	0·014	1·50	1·20	0·16	...	...	E	1250	1275
65	24	0·37	0·23	0·59	0·023	0·031	1·56	1·15	0·28	...	...	E	1325	1350
76	24	0·48	0·23	0·81	0·012	0·032	1·92	0·85	0·33	...	...	E	1275	1300
62	24	0·36	0·34	0·52	0·026	0·011	1·42	0·96	0·27	...	...	H.F.	1250	1325
30	25	0·30	0·30	0·60	0·011	0·020	2·62	0·80	0·57	...	...	E	1250	1275
54	25	0·30	0·23	0·59	0·014	0·015	2·63	0·68	0·57	...	...	E	1250	1275
79	25	0·31	0·17	0·64	0·014	0·016	2·53	0·61	0·58	...	...	E	1225	1250
31	25	0·30	0·13	0·58	0·030	0·033	2·82	0·62	0·54	...	...	O.H.	1400	burnt 1425 approx.
58	25	0·32	0·20	0·64	0·037	0·033	2·63	0·59	0·60	...	...	O.H.	1350	1375
52	26	0·43	0·28	0·62	0·010	0·012	2·78	0·65	0·60	...	...	E	1250	1300
53	26	0·43	0·21	0·72	0·029	0·028	2·43	0·66	0·60	...	...	O.H.	1250	1300
57	31	0·98	0·26	0·44	0·015	0·030	0·29	1·44	0·04	...	...	E	1275	1300
35	31	1·08	0·29	0·47	0·033	0·036	0·19	1·46	...	...	...	O.H.	1275	1300
56	31	1·01	0·21	0·40	0·034	0·038	0·12	1·40	0·08	...	...	O.H.	1275	1300
64	33	0·15	0·28	0·50	0·010	0·011	3·00	0·18	...	...	...	E	1300	1325
60	33	0·16	0·21	0·47	0·035	0·018	3·24	0·25	...	...	...	O.H.	1350	1375
15	38	0·10	0·18	0·27	0·032	0·030	4·96	...	...	...	...	O.H.	1350	...
22	39	0·14	0·16	0·37	0·008	0·012	4·13	1·13	...	...	...	E	...	1250
40	39	0·16	0·28	0·45	0·011	0·017	4·42	1·16	...	...	...	E	1250	1275
50	39	0·17	0·17	0·46	0·013	0·011	4·11	1·35	0·24	...	...	E	1275	1300
68	39	0·17	0·24	0·33	0·015	0·013	4·22	1·25	0·22	...	...	E	1250	1275
69	39	0·17	0·24	0·33	0·015	0·013	4·22	1·25	0·22	...	...	E	1250	1275
80	39	0·18	0·19	0·44	0·019	0·020	4·15	1·16	0·27	...	...	E	1275	1300
66	39	0·16	0·13	0·45	0·015	0·011	4·31	1·29	0·28	...	...	Cool refined	1300	1325
67	39	0·16	0·13	0·45	0·015	0·011	4·31	1·29	0·28	...	...		1300	1325
55	39	0·18	0·25	0·49	0·038	0·031	4·17	1·22	0·26	...	...	O.H.	1350	1375
24	40	0 21	0·31	0·56	0·014	0·012	0·20	3·01	0·52	...	...	E	1275	1300
25	40	0·19	0·27	0·53	0·014	0·013	0·31	2·96	0·41	...	...	E	1275	1300
43	40	0·27	0·25	0·59	0·018	0·014	0·26	3·13	0·53	...	...	E	1300	1325
51	40	0·19	0·26	0·50	0·015	0·010	0·35	3·01	0·40	...	...	E	1275	1300
59	40	0·25	0·19	0·47	0·020	0·013	0·25	3·07	0·53	...	...	E	1325	1350
46	45	0·57	1·90	0·91	0·050	0·030	...	...	...	...	...	O.H.	1350	1375
47	47	0·57	0·34	0·66	0·040	0·033	...	1·02	...	0·18	...	O.H.	1350	1375
20	100	0·38	0·31	1·28	0·007	0·011	1·02	0·52	0·17	...	...	E	1250	1300
72	...	0·14	trace	1·10	0·212	0·046	...	...	...	...	0·19	O.H.	1400	...
73	...	0·35	0·207	1·53	0·043	0·052	...	...	0·22	...	0·17	O.H.	1375	burnt 1400
74	...	0·25	0·112	1·22	0·027	0·020	...	...	...	...	0·16	O.H.	1400	...
12	...	0·39	0·25	0·70	0·033	0·030	1·19	...	...	...	...	O.H.	1350	...
14	...	0·39	0·24	1·18	0·046	0·038	1·70	...	...	...	...	O.H.	1350	...
18	...	0·31	0·17	0·67	0·034	0·022	...	1·00	...	...	...	O.H.	1350	...
28	...	0·35	0·19	0·59	0·024	0·031	3·16	0·47	0·26	...	...	O.H.	1350	...

Correlation between Etch and Fracture Tests.

Owing to the importance of the fracture and etch tests as means of indicating incipient overheating, they have been examined in some detail. The extent of the correlation has been determined, and also the condition of heat-treatment of the steel in which overheating is most clearly revealed.

It has been shown by Austin [4] that both the

fracture and the etch tests reveal the same granular structure. Confirmation of this is shown by Figs. 17 and 18, in which the fracture can be seen to follow the boundaries outlined by the ammonium nitrate etchant.

While it was fairly evident that the crystal boundaries revealed by these tests were those of the austenite crystals existing at the high temperatures, this fact had not been firmly established. To do this, two specimens of the same steel were heated side by side to a temperature a little above that required to induce overheating. One specimen was water-quenched and etched in the nitric–picric reagent, and the other was allowed to cool in air, after which it was fully heat-treated, and then etched in ammonium nitrate and in the nitro-sulphuric etchant. The similarity in the crystal structure shown by both specimens left little doubt that the ammonium nitrate and the nitro-sulphuric etchants outline the crystals of the austenite existing at the high temperature. Further evidence—obtained incidentally in studying other aspects of the main problem, such as the effect of cooling rate or soaking time on overheating—has amply confirmed that both the fracture and the etch tests reveal the austenite crystal boundaries.

The optimum condition of heat-treatment was determined in the following manner. A number of steels were heated to various temperatures above and below their respective overheating temperatures, and etch and fracture tests were carried out at each stage of the subsequent heat-treatment, as indicated by A, B, C, &c., in the thermal history chart shown in Fig. 4.

Referring to Fig. 4, it was found that the fracture test was of no use with specimens (1 in. in dia.) in the air-cooled condition (A), and was no better on those in the oil-quenched condition (B), unless the overheating temperature had been appreciably exceeded. The fully heat-treated condition (E) was the most satisfactory for the alloy steels. As the tempering temperature was increased to 600° C., the facets increased in number and became more clearly defined. If the normal tempering temperatures were exceeded (F), the facets became less clear, and, in steels where overheating was slight, the fracture no longer showed evidence of facets. If, however, the steel was again oil-quenched and tempered (H), the faceted structure appeared once more.

Similar experiments carried out on overheated specimens of a plain carbon steel (No. 81, *see* Table I.) gave the granular fracture only after tempering at 200° C. Other conditions of heat-treatment and higher tempering temperatures gave no indication of overheating.

It is evident, therefore, that the fracture test should be carried out on the steel only after it has been suitably heat-treated.

Regarding the etch test, it was found that the clearness of the structure obtained with the nitro-sulphuric etch was independent of the condition of heat-treatment, and was the same for all conditions from A to H.

The behaviour of the ammonium nitrate etchant was different, and followed fairly closely that of the fracture test. For example, it gave no evidence of the overheated structure in the air-cooled condition (A), but became effective after oil-quenching (B), and improved as the tempering temperature was increased to 600° C. When tempering temperatures were exceeded (F), the effectiveness of the etch decreased, and in some cases no evidence of the white boundary structure was visible. It could be revived, however, by giving the steel specimen a further oil-quenching and tempering treatment. Here again, the ammonium nitrate etch closely resembled the behaviour of the fracture test.

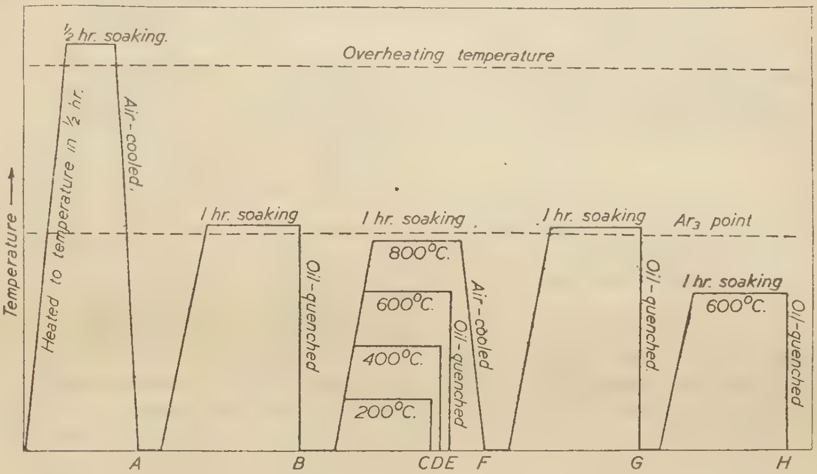


FIG. 4.—Thermal History Chart showing successive stages of heat-treatment.

With the carbon steel, the ammonium nitrate etch showed evidence of overheating after the oil-quench, and also after tempering at 200° C., but not with higher tempering temperatures. The nitro-sulphuric etch, on the other hand, was more general in its application, the black boundaries being shown in all the above conditions of heat-treatment.

One steel (No. 54, *see* Table I.) gave unusual results, for the fracture showed less evidence of overheating as the tempering temperature was increased to 600° C. Two further casts of this

Table II.—*Results of Fracture and Etch Tests.**

	Subsequent Treatment.	Type of Fracture.	Structure Obtained with Ammonium Nitrate Etch.
Steel No. 61 (3½% Ni). Heated to 1375° C., *i.e.*, 75° C. above incipient overheating temp.	As heated.	Rough.	No overheated structure.
	As quenched.	One or two facets.	Narrow white boundaries.
	T. at 200° C.	A few facets.	Some white boundaries.
	T. at 400° C.	More facets than above.	Clear white boundaries.
	T. at 600° C.	Many facets.	Clear white boundaries.
	T. at 800° C.	Fibrous, no facets.	No boundaries.
Steel No. 42 (1½% Ni–Cr–Mo). Heated to 1300° C., *i.e.*, just to the incipient overheating temp.	As heated.	Transcrystalline.	No overheated structure.
	As quenched.	An occasional facet.	No overheated structure.
	T. at 200° C.	One or two facets.	White boundaries.
	T. at 400° C.	A few facets.	White boundaries.
	T. at 600° C.	A few facets.	White boundaries.
	T. at 800° C.	Fibrous, no facets.	No overheated structure.
Steel No. 52 (2½% Ni–Cr–Mo, high-carbon). Heated to 1375° C., *i.e.*, 75° C. above incipient overheating temp.	As heated.	Transcrystalline.	No overheated structure.
	As quenched.	One or two facets.	White boundaries.
	T. at 200° C.	A few facets.	White boundaries.
	T. at 400° C.	More facets than above.	White boundaries.
	T. at 600° C.	Many facets.	White boundaries.
	T. at 800° C.	A few facets.	White boundaries.
Steel No. 51 (3% Cr–Mo). Heated to 1300° C., *i.e.*, just to the incipient overheating temp.	As heated.	Transcrystalline.	No overheated structure.
	As quenched.	One or two facets.	White boundaries.
	T. at 200° C.	A few facets.	White boundaries.
	T. at 400° C.	More facets than above.	White boundaries.
	T. at 600° C.	More facets than above.	White boundaries.
	T. at 800° C.	Fibrous, no facets.	White boundaries.
Steel No. 51 (3% Cr–Mo). Heated to 1375° C., *i.e.*, 75° C. above incipient overheating temp.	As heated.	Transcrystalline.	No overheated structure.
	As quenched.	One or two facets.	White boundaries.
	T. at 200° C.	A few facets.	White boundaries.
	T. at 400° C.	Several facets.	White boundaries.
	T. at 600° C.	Many facets.	White boundaries.
	T. at 800° C.	Several facets.	White boundaries.
Steel No. 81 (" 20 " carbon). Heated to 1350° C.	As heated.	Transcrystalline.	No overheated structure.
	As quenched.	Fibrous.	White boundaries.
	T. at 200° C.	Granular in parts.	White boundaries.
	T. at 400° C.	Fibrous.	No overheated structure.
	T. at 600° C.	Fibrous.	No overheated structure.
Steel No. 54 (2½% Ni–Cr–Mo, medium-carbon). Heated at 1375° C., *i.e.*, 75° C. above incipient overheating temp.	As heated.	Granular.	No overheated structure.
	As quenched.	Granular.	No overheated structure.
	T. at 200° C.	Granular.	No overheated structure.
	T. at 400° C.	Almost granular.	No overheated structure.
	T. at 600° C.	Many facets.	No overheated structure.
	T. at 800° C.	Several facets.	No overheated structure.

* Black boundaries were obtained in all cases with the nitro-sulphuric etch.

steel (Nos. 58 and 79, *see* Table I.) gave similar results. No explanation is offered for the behaviour of these three steels.

Results obtained with the fracture and etch tests on steels in various stages of heat-treatment are given in Table II.

As it was necessary to determine the temperature of incipient overheating for a large number of steels, ample opportunity was provided for comparing the overheating temperatures given by the fracture and the etch tests. Good agreement in the heat-treated condition was found between the nitro-sulphuric etch and the fracture test. The ammonium nitrate etch was not, in all cases, quite as efficient, and with this etchant it was necessary to heat some steels to slightly higher temperatures before there was any evidence of overheating; however, the divergence was never more than 25° C. This reagent was also found to be unsatisfactory with the four En 25 steels given in Table I.; clear white boundaries were not shown, even when these steels were appreciably overheated.

Measurement of Overheating Temperature.

On the basis of the fracture and etch tests, the overheating temperatures of a number of steels have been determined. The method was as follows. Specimens of each steel were heated to successively higher temperatures differing by

intervals of 25° C. The specimens were then examined as described below, and the lowest temperature which gave signs of overheating, in either the fracture or the etch test, was taken as the overheating temperature. So far, the temperature range has not been taken beyond 1375° C., except for a few steels. It is intended to extend this range as opportunity allows.

Specimens 8 in. long and 1 in. in dia. were heated to the required temperature in approximately 30 min.; this temperature was held for a further 30 min., after which the specimens were air-cooled. A 1-in. length was then broken from one end, after suitably nicking the specimen, and reserved for examination of the fracture and microstructure. The remainder of the specimen was fully heat-treated and a second 1-in. length was removed by nicking and fracturing. This second specimen provided the fracture test-piece; a round Izod test-piece was turned from the remaining length of bar and the impact value measured.

By this procedure it was possible to follow the progress of overheating, as shown by the fracture and etch tests, and in addition the effect of progressive overheating on the Izod impact value.

The majority of the specimens were heated with an atmosphere of the following composition flowing through the muffle tube :

N_2.	CO_2.	H_2O.	O_2.
78%	10%	8%	4%

This mixture is typical of most furnace atmospheres in practice, and represents conditions where the fuel is burned with more air than is required for complete combustion. When it was discovered that the composition of the atmosphere had no appreciable influence on the overheating properties of the steel, an atmosphere consisting of nitrogen with 1–3% of oxygen and 2% of water vapour was used, as this gave less oxidation, and consequently minimized the problem of dealing with the molten oxide at the higher temperatures. The velocity of gas flow through the muffle tube was 10 ft./sec.

Figs. 19 to 25 show the fractured surfaces of a series of specimens originally heated to the temperatures indicated, and subsequently heat-treated, as previously described, before breaking. First signs of overheating are indicated by the appearance of facets as shown in Fig. 20. It will be noted how these facets increase in number and size as the incipient overheating temperature is exceeded, until a full granular structure is obtained. These changes represent the behaviour of most of the steels, though with a few there was a sudden change at the overheating temperature from the fibrous structure (Fig. 19) to the completely granular fracture. The earliest appearance of the facets was accompanied by the appearance of polygonal boundaries, or traces of boundaries, in the nitro-sulphuric etch. In one or two steels evidence of overheating was discernible in the etch test a little earlier than in the fracture test; the difference in temperature, however, was well within 25° C.

Occasionally some difficulty was experienced in these incipient stages of overheating in interpreting the nitro-sulphuric etch. Because of the tendency for etch-pits to be developed and non-metallic inclusions to be dissolved, the first indication of a boundary was often a series of black dots instead of a continuous line. On these few occasions the result of etching a second specimen, which had been heated to 25° C. higher, was a useful guide in interpreting the etched structure of the first.

The overheating temperatures of a number of steels are given in Table I., together with their compositions and methods of manufacture.

From these figures there would appear to be no clear relationship between composition and overheating temperature. Steels with almost the same content of the elements normally specified, often showed a wide variation in overheating tendencies. This is in line with industrial experience, where consecutive casts of steel made from the same stocks of raw materials have sometimes shown considerable differences in overheating properties.

The open-hearth steels, with one or two exceptions, have a higher overheating temperature than the electric steels, and this also would seem to be confirmed by practice, as overheating troubles are less frequent with open-hearth steels.

As far as composition is concerned (Table I.), the main difference between the open-hearth and the electric steels is in the sulphur and phosphorus contents. It is also to be expected that the electric steels would contain less residuals, and possibly a lower oxygen content, than the open-hearth steels.

In Figs. 5(*a*) and 5(*b*), respectively, the phosphorus and sulphur contents of the steels have been plotted against the overheating temperature. The degree of scatter in Fig. 5(*a*) is too great to admit of any relationship being established. In Fig. 5(*b*) the scatter is also very great, but the points appear to fall generally into two groups, according to the method of manufacture. The line *AB* (Fig. 5(*b*)) almost completely separates the open-hearth from the electric steels. Whether this distribution of points is due to some fundamental difference inherent in the two methods of steelmaking, or to a relationship between the sulphur content and overheating tendencies, is at present problematical.

Attention was drawn to the oxygen content when it was found that two steels (Nos. 30 and

31), made to the same specification, differed widely in overheating properties and also in oxygen content. Examination of five further steels gave interesting results :

Steel No.	Method of Manu-facture.	Incipient Over-heating Temp., ° C.	Oxygen, %.	Nitrogen, %.
30	E *	1275	0·002	0·006
40	E	1275	0·003	0·011
52	E	1300	0·003	0·008
50	E	1300	0·004	0·007
53	O.H.	1300	0·005	0·003
55	O.H.	1375	0·009	0·006
31	O.H.	1425 (approx.)	0·013	0·004

* E = Electric furnace.

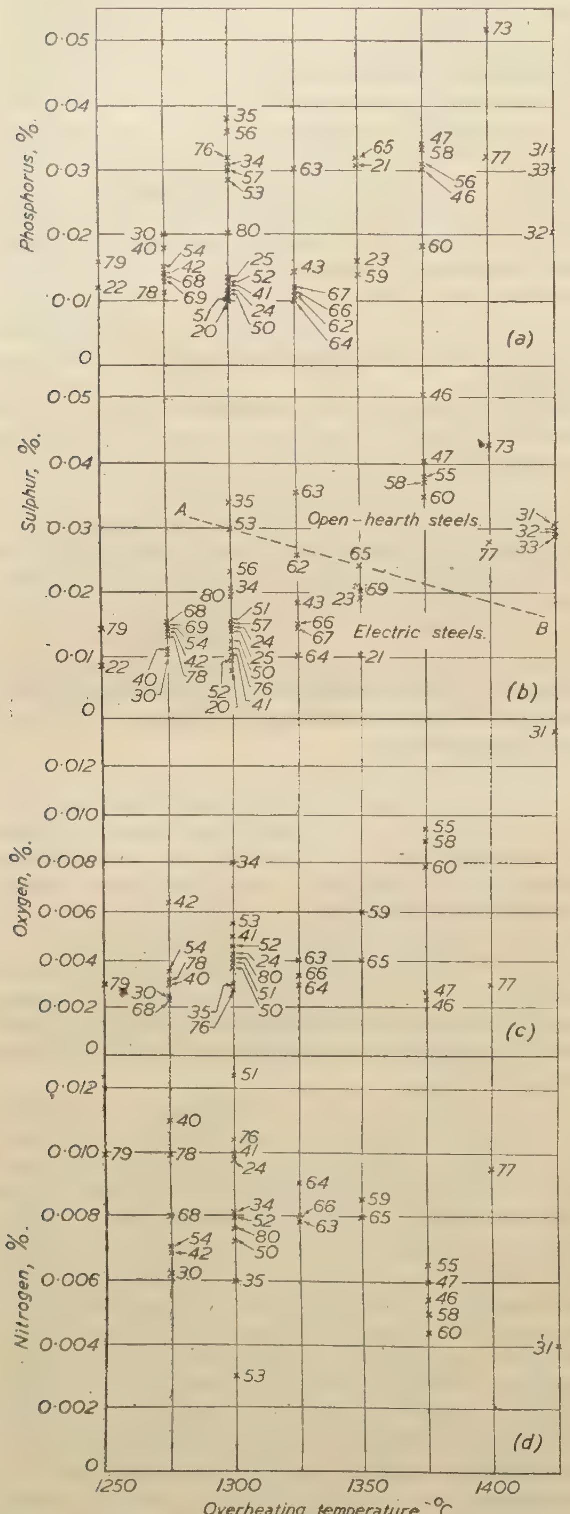


FIG. 5.—Overheating Temperature Plotted against (*a*) Phosphorus, (*b*) Sulphur, (*c*) Oxygen, and (*d*) Nitrogen Contents.

These figures suggested a possible connection between the oxygen content and overheating tendencies, a high overheating temperature being associated with a high oxygen figure. It was thought advisable to examine this relationship further, and twenty-three steels were chosen from Table I. and analysed for oxygen and nitrogen. The gas analyses are given in Table III., and the oxygen content plotted against the overheating temperature is shown in Fig. 5(*c*). The results are disappointing in view of the promise given by the initial tests. A close correlation was not expected, however, as a wide range of steels was included in Fig. 5(*c*). There is also the possibility that the oxygen content and the overheating temperature are both governed by some other factor, in which case the relationship would be accidental and therefore could not be exact.

A statistical examination of the distribution of the points shown in Figs. 5(*b*) and 5(*c*) gave the following correlation coefficients :

Between overheating temperature and sulphur content = +0·70.
Between overheating temperature and oxygen content = +0·57.
Between overheating temperature and sulphur-plus-oxygen content = +0·76.

This indicates a significant relationship. No relationship is apparent between the nitrogen content and overheating temperature (Fig. 5(*d*)).

Earlier theories have attributed overheating phenomena to the envelopment of the austenite crystal by a film of non-metallic material; steels with a large amount of non-metallic inclusions would therefore be expected to have pronounced overheating tendencies. The present investigation has not only shown this to be false, but has clearly demonstrated that steels with a high inclusion content are those possessing a high overheating temperature.

The difficulty in obtaining an exact quantitative measurement of the non-metallic inclusions in steel has been stressed in earlier papers and is fully appreciated here. The Fox inclusion count was adopted as a means of obtaining comparative results, and, while the authors do not claim to

TABLE III.—*Overheating Temperature and Gas Analysis of a Selection of Steels Shown in Table I.*

Sample No.	En Specification.	Method of Manufacture.	Overheating Temp., ° C.	Oxygen, %.	Nitrogen, %.
77	3	E	1400	0·003	0·009
78	22	E	1275	0·003	0·010
41	22	E	1300	0·005	0·010
63	22	O.H.	1325	0·004	0·004
42	24	E	1275	0·006	0·007
34	24	E	1300	0·008	0·008
76	24	E	1300	0·003	0·010
65	24	E	1350	0·004	0·008
79	25	E	1250	0·003	0·010
54	25	E	1275	0·003	0·007
30	25	E	1275	0·002	0·006
58	25	O.H.	1375	0·009	0·005
31	25	O.H.	burnt 1425	0·013	0·004
52	26	E	1300	0·003	0·008
53	26	O.H.	1300	0·005	0·003
35	31	O.H.	1300	0·003	0·006
64	33	E	1325	0·003	0·009
60	33	O.H.	1375	0·008	0·004
40	39	E	1275	0·003	0·011
68	39	E	1275	0·002	0·008
50	39	E	1300	0·004	0·007
80	39	E	1300	0·004	0·007
66	39	E (cool refined)	1325	0·004	0·008
55	39	O.H.	1375	0·009	0·006
24	40	E	1300	0·004	0·010
51	40	E	1300	0·003	0·012
59	40	E	1350	0·006	0·008
46	45	O.H.	1375	0·002	0·005
47	47	O.H.	1375	0·003	0·006

have had much experience with this method of examination, the curve obtained by plotting the Fox inclusion count against the incipient overheating temperature has been checked by two observers and the agreement is satisfactory. The relationship is shown in Fig. 6(*a*), while the modified count, as suggested by Hatfield and Giles,[6] is plotted against the incipient overheating temperature in Fig. 6(*b*). In addition, four steels with exceptionally high inclusion counts showed no evidence of overheating even at 1400° C. :

Steel No.	Inclusion Count.
70	174
71	240
72	240
74	155

At the present stage in this investigation, it is difficult to offer any interpretation of the results shown in Figs. 6(*a*) and 6(*b*). No evidence has been obtained to suggest how the non-metallic inclusions could have a direct or indirect effect in suppressing overheating tendencies in steel, or why freedom from inclusions should give a low overheating temperature, yet this would appear to be so. However, a conclusion which may safely be drawn at this juncture is that a method of steel manufacture which gives a high inclusion count will also give a steel with a high overheating temperature, and conversely.

These results do, nevertheless, discredit theories connecting overheating tendencies with the presence of inclusions and, in this connection, it may be mentioned that a high-sulphur free-cutting steel (No. 71, Table I.) showed no tendency for the inclusions to form boundary films on heating to 1400° C., and in a leaded steel (No. 74, Table I.) heated to 1375° C., no evidence of film formation around the austenite crystals could be discovered.

Effect of Overheating on Izod Impact Strength and Tensile Properties of Alloy Steels.

It is well known that burnt steels are exceedingly brittle, and since both overheating and burning give a form of intergranular weakness, it was thought that the progress of overheating could be followed by measuring the Izod impact values of a series of specimens heated to successively higher temperatures well into the overheating range. The specimens used for determining the incipient overheating temperature were suitable for this purpose.

It was appreciated that, from the practical point of view, the most important mechanical property to be considered was the fatigue strength. Facilities at the authors' laboratory were not suitable for carrying out large numbers of fatigue tests, but it is understood that this property is being studied at another laboratory.

At the present stage of this work the temperature range has not been taken beyond 1375° C., except in a few cases. It is proposed to use higher temperatures as the investigation proceeds.

Specimens for the Izod tests were fully heat-treated, *i.e.*, oil-quenched, and tempered at 600° C.

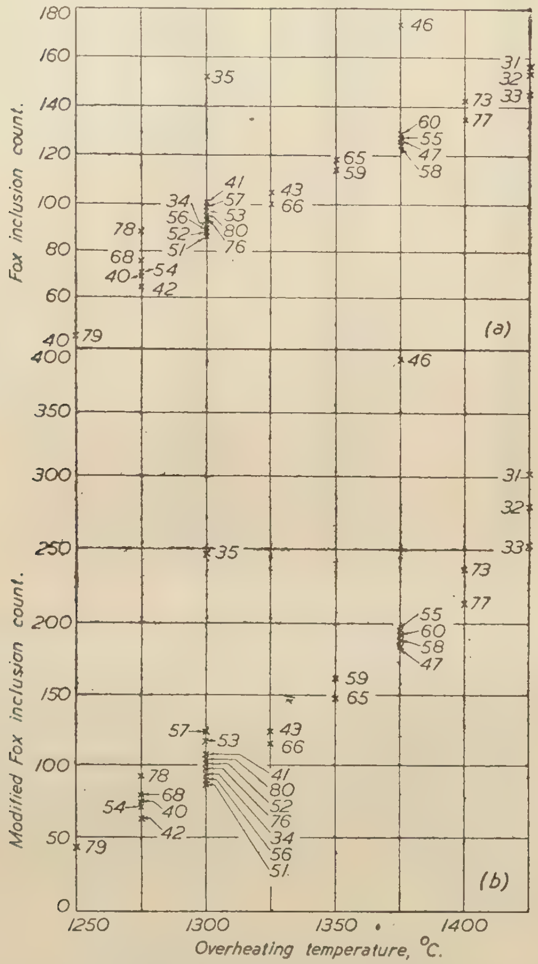


FIG. 6.—Incipient Overheating Temperature plotted against (*a*) the Fox Inclusion Count and (*b*) the Modified Fox Inclusion Count. (Numbers refer to samples.)

It was necessary to control the tempering temperature within very narrow limits to ensure the same hardness figure in each series of test-pieces. A large lead bath, thermostatically controlled, was found convenient for this work. All specimens were held at the tempering temperature for 1 hr.

Some typical results are shown in Fig. 7. The curves are shown as full lines above the overheating temperature and as dotted lines below it. Wherever possible, electric and open-hearth steels of the same En specification are included in the same graph, as significant differences have been observed between similar types of steel. The overheating temperature as determined by the fracture and the etch tests is indicated by arrows.

It will be seen that with the electric steels the Izod value begins to fall immediately overheating occurs, but this is not always the case with the open-hearth steels. The fall in Izod value with overheating temperatures up to 1375° C. is

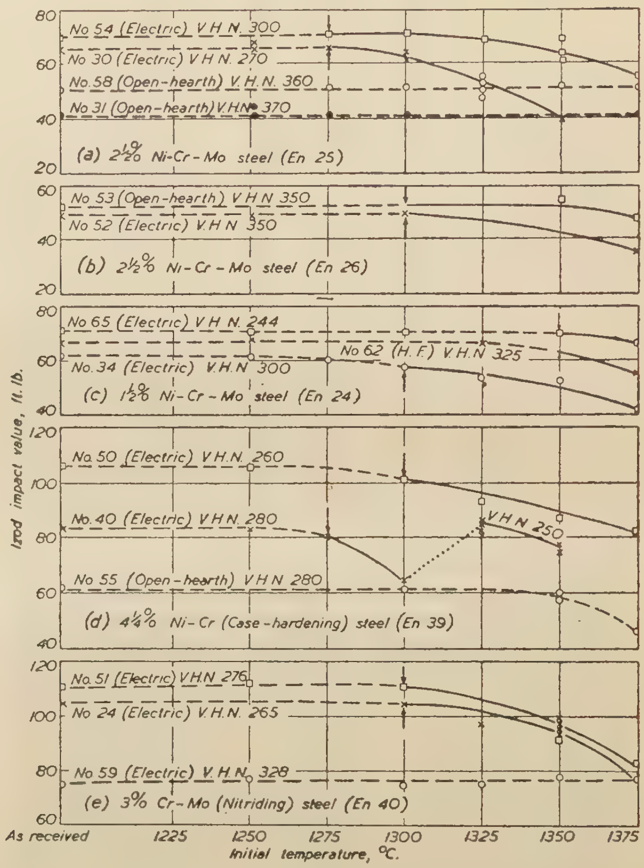


FIG. 7.—Effect of Overheating on Izod Impact Values. Arrows indicate overheating temperatures.

gradual in all the steels so far examined, but it should not be concluded that overheating can not induce a high degree of embrittlement, since specimens have been obtained in this investigation in which the Izod value had been reduced, by overheating, from 100 to 10 ft.lb.

The break in the curve for steel No. 40 in Fig. 7(*d*) was caused by a failure of the thermostat in the tempering bath. This curve is included merely to illustrate the need for accurate temperature control in the tempering operation.

One interesting feature brought out in these tests was the lower Izod value of the open-hearth steel as compared with the corresponding electric steel. This would seem to be due to the fact

TABLE IV.—*Effect of Overheating on Tensile Properties.*

Sample. No.	Sample. Specification.	Original Temp., ° C.	Yield Point, tons/sq.in.	Ultimate Strength, tons/sq.in.	Elongation (on 2 in.), %.	Reduction of Area, %.
42	En 24 ($1\frac{1}{2}$% Ni–Cr–Mo).	1375	57·1	64·1	20	46
		1350	58·0	65·1	19·5	48
		1325	58·7	65·8	20	50
		1300	57·4	64·7	21·5	54
		1275	57·7	65·0	21·5	57
		1250	58·4	64·8	22	56
		As received	58·6	65·6	21·5	57
43	En 40 (3% Cr–Mo nitriding).	1375	49·3	57·8	23·5	60
		1350	48·3	57·0	24	64
		1325	46·7	55·4	25	66
		1300	46·4	56·5	25	65
		1275	48·4	58·5	24	66
		1250	50·0	59·7	24	66
		As received	52·1	60·3	25·5	68
79	En 25 ($2\frac{1}{2}$% Ni–Cr–Mo, medium carbon).	1375	65·2	69·5	13·5	39
		1350	65·5	70·3	16·5	44
		1325	64·8	69·8	18	51
		1300	64·5	69·9	19·5	53
		1275	65·1	69·7	18·5	54
		1250	63·5	69·8	19·5	54
		1225	65·3	70·2	19	55
		As received	63·5	68·6	18	60
80	En 39 ($4\frac{1}{4}$% Ni–Cr case-hardening).	1375	46·7	53·8	22·5	57
		1350	47·4	54·1	23·5	61
		1325	52·7	59·3	23·5	60
		1300	47·4	54·0	25	67
		1275	46·0	54·1	25·5	68
		As received	47·8	54·2	24	68

that the same oil-quenching and tempering treatment gives a lower hardness in the electric steel than in the open-hearth steel. One pair of steels (Nos. 52 (E) and 53 (O.H.)) were exceptional in

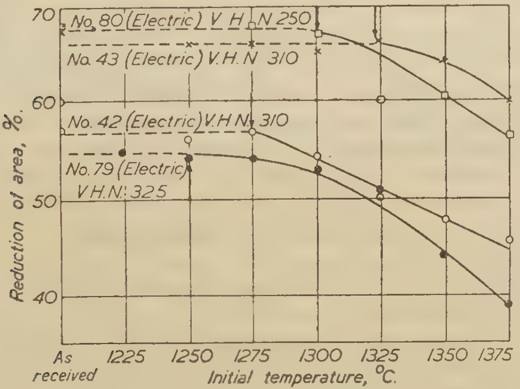


FIG. 8.—Effect of Overheating on Ductility (Reduction of Area). Arrows indicate overheating temperatures.

this respect, and gave the same hardness figure and similar Izod values after heat-treatment (Fig. 7(*b*)). Steel No. 53 has an unusually low oxygen content for an open-hearth steel. This problem is being studied further, as it suggests a possible connection between the oxygen content of a steel and its resistance to tempering.

The effect of overheating on the tensile properties of four steels has also been examined and the results are shown in Table IV. As with the Izod tests, the specimens were heat-treated after air-cooling from the high temperatures.

Austin [4] has stated that the ductility, as measured by the elongation and reduction of area, is reduced by overheating The present results are in agreement with this statement so far as the reduction of area is concerned, and this fall with increasing degree of overheating is illustrated in Fig. 8. The tensile strength and elongation were not appreciably affected after overheating at temperatures up to 1375° C.

Furnace Conditions.

(a) *Composition of Furnace Atmosphere.*

It has been found that for the range of temperatures so far investigated, *i.e.*, up to 1375° C., the overheating properties of steels are in no way influenced by the atmosphere in which they are heated.

The atmospheres investigated included four which were made up to represent possible con-

ditions occurring in practice, details of which are given below:

(a) To represent almost complete combustion of the fuel.
(b) As (a), but with a fuel having a high sulphur content.
(c) To represent conditions obtained with excess air for combustion.
(d) As (c), but with a fuel having a high sulphur content.

	N_2, %.	H_2O, %.	CO_2, %.	CO, %.	SO_2, %.	O_2, %.
(a)	79	10	10	1·0	...	...
(b)	79	10	10	1·0	0·20	...
(c)	78	8	10	...	...	4·0
(d)	78	8	10	...	0·20	4·0

The above atmospheres simulate fairly closely the products of combustion of producer gas, and the sulphur dioxide content would be obtained by using a coal containing 3% of sulphur.

As far as general oxidation is concerned, the type of oxide formed is very different in changing over from an atmosphere containing carbon monoxide to one with free oxygen. The presence of sulphur dioxide introduces a further important change in atmospheres containing no free oxygen, but it has no important effect when oxygen is present.

In addition, an atmosphere of nitrogen containing 2–3% of oxygen and 2% of water vapour was used. A small number of comparisons were also made between these atmospheres and purified nitrogen and hydrogen.

In the first place, specimens were heated to temperatures slightly below, and slightly above, the overheating temperature in the different atmospheres. Each steel gave the same overheating temperature irrespective of the atmosphere, and where this had not been attained in any one atmosphere, the same was true for the others. At higher temperatures, where overheating was well established, again no appreciable difference could be detected in changing from one atmosphere to another, although it is not as easy to assess differences in these conditions as in the early stages of overheating. In the few instances where Izod determinations were carried out, they confirmed these findings (*see* Table V.).

The steels selected for comparison in different atmospheres at 1375° C., were:

	Overheating Temp., ° C.
No. 42 (1½% Ni–Cr–Mo)	1275
No. 43 (3% Cr–Mo)	1325
No. 52 (2½% Ni–Cr–Mo)	1300
No. 55 (4¼% Ni–Cr)	1375

The atmospheres used were (a), (b), (c), and nitrogen containing 2–3% of oxygen and 2% of water vapour.

The results obtained with these steels again showed no significant differences in changing from one atmosphere to another. In all cases a change in temperature of 25° C. produced a far greater effect than did a change of atmosphere. Jominy [3] has stated that in changing from a reducing atmosphere (containing carbon monoxide) to an oxidizing atmosphere, the burning temperature of steel was decreased by approximately 50° C. The present investigation has shown that overheating is not affected in this way.

(b) *Soaking Time.*

The effect of different soaking times on the development of the overheated structure has been examined.

In one series of experiments, bars of 1 in. dia. were placed in the furnace and heated to 1350° C. in 30 min., and one specimen was removed after each of the following soaking times: 5 min., 20 min., 1½ hr., and 5½ hr. After withdrawal from the furnace the specimens were air-cooled and fully heat-treated before examination. The fractures obtained in one typical series are shown in Figs. 26 to 29. All show evidence of overheating, even the specimen soaked for only 5 min. The grain growth occurring at the soaking temperature is shown by the increase in size of the crystalline facets. It will be noted that as the structure becomes coarser the fracture includes a larger proportion of the weak boundary.

Evidence of overheating was also found in

TABLE V.—*Izod Impact Values of Steels Heated in Different Furnace Atmospheres.*

Sample No.	Specification.	Overheating Temp., ° C.	Temp. Attained by Specimen, ° C.	Izod Impact Value, ft.lb.			
				Atmosphere (a) (Reducing).	Atmosphere (b) (Reducing + SO_2).	Atmosphere (c) (Oxidizing).	Atmosphere (d) (Oxidizing + SO_2).
30	En 25 (2½% Ni–Cr–Mo).	1275	1250	67 *	67 *	...	...
,,	,, ,,	,,	1300	62½	...	63	...
,,	,, ,,	,,	1350	...	44	...	45
31	,, ,,	1425	1350	...	45 *	...	43 *
58	,, ,,	1375	1325	54 *	56 *	55 *	51 *
40	En 39 (4¼% Ni–Cr).	1275	1325	82	86	83	85
41	En 22 (3% Ni).	1300	1325	77	76	73	74

* Specimen not overheated.

small specimens placed in a furnace at 1350° C. for only 5 min. The rapidity with which overheating can occur has also been demonstrated in specimens heated by induction methods. It has been claimed that overheating has been found in steels heated for less than 1 min. This fact would appear to be of importance in industry, where flash heating may occur.

Overheating and Grain-Size.

It has been suggested on various occasions that overheating is in some way connected with, or accentuated by, the formation of large austenite grains at the high temperatures concerned. No precise information has been brought forward to substantiate this theory, and it soon became evident in the present investigation that there was no relationship between the austenitic grain-size and the overheating temperature.

An examination of the grain-size determinations shown in Table VI. and of the corresponding overheating temperatures amply demonstrates this finding. Determinations were made on specimens heated for 30 min. at the overheating temperature (*see* Table VI.).

Table VI.—*Overheating Temperature Compared with Austenitic Grain-Size.*

Sample No.	En Specification.	Method of Manufacture.	Overheating Temp., ° C.	A.S.T.M. Grain-Size.
40	39	E	1275	−3
54	25	E	1275	−2
42	24	E	1275	−2
41	22	E	1300	−3
51	40	E	1300	−1
50	39	E	1300	−1
52	26	E	1300	0
53	26	O.H.	1300	+1
34	24	E	1300	+2
55	39	O.H.	1375	−1

McQuaid-Ehn tests were also carried out on a suitable selection of steels, and here again the results, shown in Table VII., revealed no relationship between the McQuaid-Ehn grain-size and the overheating temperature. It will be seen that steels with the same overheating temperature give very different grain-size figures, the converse also being true.

Table VII.—*Overheating Temperature Compared with McQuaid-Ehn Grain-Size.*

Sample No.	En Specification.	Method of Manufacture.	Overheating Temp., ° C.	McQuaid-Ehn Grain-Size.
54	25	E	1275	7
30	25	E	1275	5
76	24	E	1300	7
52	26	E	1300	5
53	26	O.H.	1300	4
41	22	E	1300	4
63	22	O.H.	1325	3
65	24	E	1350	8
58	25	O.H.	1375	6
31	25	O.H.	... *	3

* Not overheated at 1400° C.

Importance of the Rate of Cooling After Overheating.

Experiments in which steel specimens were allowed to cool at different rates from well above their overheating temperatures have given most interesting results.

It was found, in the first place, that specimens which were cooled in the furnace from well above the overheating temperature, gave little or no evidence of overheating, while, if the specimens were allowed to cool in air, very definite overheating was observed. The rate of cooling in the laboratory furnace was approximately 3°C./min. in the high-temperature range.

Quenching from these high temperatures also tended to suppress overheating.

When nickel, nickel–chromium, and nickel–chromium–molybdenum steels were furnace-cooled from temperatures as high as 1375° C. (even with a steel possessing an overheating temperature as low as 1250° C.), overheating was completely suppressed in some cases, and in the others it was only very slight; chromium–molybdenum steels, however, were not so amenable to this treatment, though even here the overheating was largely suppressed.

It was later discovered that the temperature range through which slow cooling was necessary, extended only from the high temperature to which the steel had been heated, down to slightly below the overheating temperature. Once below this lower temperature, the cooling rate was no longer important, apart from the fact that in the region of 1250–1100° C. the small amount of diffusion occurring in the slowly cooled specimen would tend to remove any slight degree of overheating remaining after the slow cooling in the higher range.

Further experiments showed that when, for example, a steel with an overheating temperature of 1300° C. was heated to 1375° C., and allowed to cool in the furnace to 1325° C. before withdrawing for air-cooling, the resultant degree of overheating was about the same as that found in a specimen heated to only 1325° C. and air-cooled from that temperature. These results are summarized in Fig. 9.

Finally, when specimens were air-cooled from the high temperature down to approximately 1000° C. and then slowly cooled to room temperature, the overheating was similar to that found in specimens which had been completely air-cooled.

It is evident from these results that the mechan-

ism which results in overheating operates only while the steel is cooling from the high temperature to approximately the overheating temperature, or slightly below it.

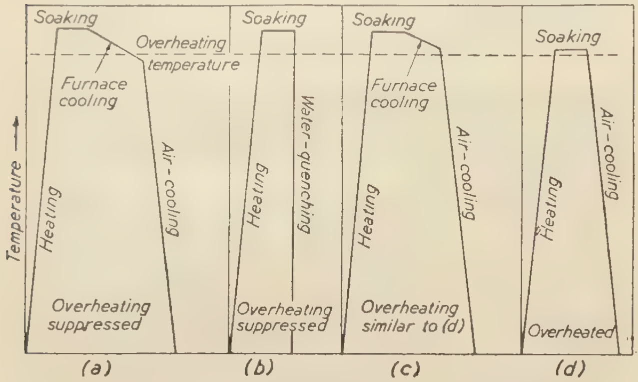


FIG. 9.—Effect of Cooling Rate on Overheating.

While quenching from the high temperatures will not have any application in practice, it may be advisable to point out that when specimens are broken in the quenched condition, they give a very striking granular fracture. The facets have a mirror-like appearance, as shown in Fig. 30, and can be easily distinguished in this way from the normal overheated fracture. On oil-quenching and tempering these quenched specimens, the fracture becomes fibrous (Fig. 31).

Resuscitation of Overheated Steel.

In practice it is sometimes possible to reclaim overheated steels by subjecting them to a prolonged normalizing treatment at a temperature between 900° and 1150° C. or by repeating the usual normalizing treatment a number of times.

In order to judge the relative merit of these methods, bars of the three following steels were air-cooled from 1375° C. and heat-treated in the usual manner :

	Overheating Temp., ° C.
No. 50 (4¼% Ni–Cr) . . .	1300
No. 51 (3% Cr–Mo)	1300
No. 52 (2½% Ni–Cr–Mo) . . .	1300

Fracture tests showed a considerable degree of overheating in each steel.

Specimens from these overheated bars were then given three normalizing treatments at 900° C. of 1 hr. each, after which they were heat-treated and fractured. No improvement was found in any of the steels. Normalizing for 1 hr. at 1100° C. also had very little effect, but 6 hr. at this temperature brought about a marked improvement in the nickel–chromium and nickel–chromium–molybdenum steels. No appreciable change could be seen in the fracture of the chromium–molybdenum steel.

It was found in similar tests that 1 hr. at 1200° C. gave about the same result as 6 hr. at 1100° C. The chromium–molybdenum steel did not respond as well as the other two to this normalizing treatment.

In view of the results obtained by the slow cooling of steels from 1375° C. (described in the previous section), it was thought that resuscitation might be more effective if the overheated steels were given this slow-cooling treatment. Accordingly, specimens from the overheated bars were heated to 1375° C. and allowed to cool in the furnace (3°C./min.) to 1250° C., after which they were air-cooled, heat-treated, and fractured. The nickel–chromium and the nickel–chromium–molybdenum steels showed only the slightest trace of overheating and, while the fracture of the chromium–molybdenum steel still showed some facets, there was a considerable improvement. The same treatment applied to an overheated specimen of steel No. 54 (2½% Ni–Cr–Mo) completely removed all trace of overheating as revealed by the fracture.

In a recent experiment, Izod tests were carried out on specimens of steel No. 79 at each stage in the following series of treatments. As usual, the Izod test was carried out on the specimens after final oil-quenching, and tempering at 600° C. :

Pretreatment.	Izod Value, ft. lb.
(1) As-rolled	74
(2) Overheated by heating to 1375° C., A.C.	52
(3) Overheated by heating to 1375° C., F.C.* to 1250° C., A.C. . . .	67
(4) Overheated by heating to 1375° C., A.C. (as in (2)), reheated to 1375° C., F.C. to 1250° C., A.C. . . .	68

* F.C. = Furnace-cooled.

It will be seen that the Izod value which had been reduced by overheating to 52 ft. lb. was brought back to 68 ft. lb. by the slow-cooling treatment, and it is probable that if the slowly cooled specimens ((4) *above*) had been given a grain-refining treatment, the improvement would have been greater.

It now remains to test this method with steels which have been considerably embrittled by overheating, and experiments along these lines are being carried out.

Some idea of the improvement possible by this method of slow cooling may be obtained from a comparison of Figs. 32 and 33. The former shows the fracture of a specimen of overheated nickel–chromium–molybdenum steel submitted by a works, and Fig. 33 shows the fracture obtained after this specimen had been reheated to 1375° C., furnace-cooled to 1200° C., then air-cooled, and finally oil-quenched and tempered as usual. The difference in the two fractures is very pronounced.

No claims are made for a slow cooling rate of

3°C./min. This happened to be the rate of cooling in the muffle tube in the laboratory furnace.

Hot Working.

Steel bars 1 in. in dia. were heated to 1375° C. (75° C. above the overheating temperature) and hammered into flats of $\frac{1}{2}$, $\frac{1}{4}$, and $\frac{1}{8}$-in. thickness, respectively. The hammered sections were air-cooled and heat-treated in the normal manner.

The fracture and the etch tests showed evidence of overheating, the facets and polygonal boundaries becoming flattened ellipses as the deformation increased, which to some extent suggested a smaller degree of overheating than was shown in the absence of hot working. The flow lines in a rolled section have no influence on the polygonal structure, as is shown very clearly in Fig. 34. This photomicrograph is of interest because it demonstrates in a simple manner that grain growth at the high temperature is completely unaffected by the flow lines or rolled structure of the steel.

Problems under investigation at the present moment include the effect of overheating on isothermal transformation, and the importance of residuals, finishing conditions, and deoxidants used in the steelmaking process.

Mechanism of Overheating.

While much work still remains to be done before the mechanism of overheating is completely understood, results obtained in the present investigation have brought to light a certain amount of indirect evidence relating to this problem.

In the first place they have established the fact that overheating is an inherent property of the steel, and not simply the result of a mechanical envelopment of the austenite grains by the fusion of non-metallic constituents; nor is it caused by films produced by preferential oxidation of alloying elements such as chromium. These theories are proved untrue by (*a*) the possibility of resuscitation, and (*b*) the fact that different tempering temperatures produce different types of fracture. With regard to non-metallic constituents, it has been found that it is those steels with a high inclusion content which have a high overheating temperature.

The suppression or removal of overheating by extreme rates of cooling through the overheating range indicates that the changes in the austenite crystal which give rise to overheating take place during the cooling through this range, *i.e.*, from the temperature to which the steel has been heated, down to the overheating temperature.

The reappearance of the austenite boundary in the granular fracture and etched structure of an overheated steel can be taken as evidence of a difference in composition between the boundary and the main body of the austenite crystal. The mechanism of overheating must therefore involve a diffusion process within the austenite grain. It is not yet clear what the diffusing element or elements are, nor whether diffusion is to, or from, the boundary.

This change in composition produces a boundary which does not possess the same degree of response to heat-treatment as the remainder of the crystal. This is demonstrated by the fact that fracture occurs more readily along these boundaries as the steel is toughened by progressive heat-treatment.

It may also be explained that although the fracture of overheated steel has all the appearances of being intergranular, it is not produced by the separation of crystals. In the final heat-treated condition the structure of the steel is sorbitic, but in this sorbite there is a network of boundaries which are of a definite thickness, as shown by Fig. 35, and through which fracture occurs.

Unfortunately it has not yet been possible to compare in overheated steel the hardness of the boundary with that of the main body of what was the austenite crystal, as the hardness measuring instruments are too coarse. In one sample, in which incipient burning had occurred, the polygonal boundaries after normal heat-treatment gave a Vickers hardness number of 401, while, away from the boundary, the hardness was 320. If this is also found to be the case with overheated specimens, then it may be stated that the diffusion produces a boundary which is more resistant to the influence of tempering than is the remainder of the austenite grain.

Further understanding of the mechanism of overheating must await additional experimental evidence.

Conclusions.

The investigation is not complete, but results obtained to date make possible the following conclusions :

(1) Overheating is an inherent property of a steel, and it occurs in a temperature range extending upwards from 1250° C. It is indicated by the appearance of facets in the fracture (preferably that produced by impact), and also by special etching reagents.

(2) Overheating results from diffusion processes within the austenite grain, which operate during cooling through the overheating range. The rate of cooling has an important influence on the development of the overheated structure.

(3) Steels made to the same specification exhibit widely different overheating temperatures, electric steels generally having a lower

overheating temperature than those made in the open-hearth furnace.

(4) Steels with a low inclusion content also possess a low overheating temperature.

(5) The composition of the furnace atmosphere has no influence on the overheating properties of steel.

(6) The impact strength and tensile properties are not seriously impaired in the initial stages of overheating.

(7) Resuscitation of overheated steels by a slow-cooling treatment through the overheating range, has been found to be more effective than the methods at present in use.

Acknowledgments.

The authors wish to thank Professor D. T. A. Townend for the provision of facilities and for encouragement throughout this work. Through the kindness of Mr. H. H. Burton, all the Izod tests referred to in the paper were carried out by the Research Department of the English Steel Corporation, Ltd. They would like to express their indebtedness to the Alloy Steels Research Committee for financial assistance, and to the members of the Committee for helpful discussion, and for the provision of steels; also, to Mr. G. E. Speight, B.Sc., A.R.I.C., and members of the Gaseous and Non-Metallic Inclusions Sub-Committee who carried out the gas analyses of the steels given in Table III.

References.

1. Stansfield: *Journal of The Iron and Steel Institute*, 1903, No. II., p. 433.
2. Stead: *Journal of The Iron and Steel Institute*, 1915, No. I., p. 398.
3. Jominy: *Transactions of the American Society for Steel Treating*, 1929, vol. 16, p. 298.
4. Austin: *The Iron and Steel Institute*, 1936, *Special Report No.* 14, p. 189.
5. "Bibliography on the Burning and Overheating of Steel." *The Iron and Steel Institute*, 1944, *Bibliographical Series*, No. 10.
6. Hatfield and Giles: *Journal of The Iron and Steel Institute*, 1940, No. II., p. 237 P.

[This paper was discussed jointly with the preceding one by H. J. Merchant on "Some Aspects of the Overheating of Steel Drop-Forgings" and the following three by W. E. Goodrich on "Overheating and Burning of Nickel–Chromium–Molybdenum Steel," by F. C. Thompson and L. R. Stanton on "The Effect of Oxygen on the Isothermal Transformations of Steel, and a Suggested Test for Burning," and by J. Woolman and H. W. Kirkby on "Some Experiments on Overheating."]

OVERHEATING AND BURNING OF NICKEL–CHROMIUM–MOLYBDENUM STEEL.*

By W. E. GOODRICH, M.Met., A.M.I.Mech.E. (Messrs. William Beardmore and Co., Ltd., Glasgow).

(Figs. 1 to 15 = Plates XVI. and XVII.)

Paper No. 20/1946 *of the Alloy Steels Research Committee.*

Synopsis.

Occasionally, fractured test-pieces removed from forgings for routine inspection have disclosed small areas of granular facets, which some inspectors have interpreted as indicative of "burnt" steel. More conservative opinion, however, has regarded these areas as possible signs of "overheating," and has inclined to the view that the evidence of such a condition may be masked by slow rates of cooling while, on the other hand, signs of overheating, as judged by fractures, may occur in material which has not, in fact, been overheated. A series of experiments were therefore conducted on sections machined from a nickel–chromium–molybdenum–vanadium steel forging, the sections being heated to initial temperatures varying between 1250° *and* 1400° *C. and subjected to various cooling treatments, in some cases followed by a further standard oil-hardening and tempering operation. Afterwards, the specimens were fractured and their fractures and metallographic structures, in the various heat-treated conditions, are described.*

It has been shown that a repetition of normal oil-hardening and tempering treatments, or slow cooling from overheating temperatures, can appreciably reduce, and in many cases entirely eliminate, the abnormal granular type of fracture. All the evidence obtained indicated that it was necessary to cool fairly rapidly through the upper critical range to create conditions favourable for the formation of the granular facets, and even then tempering temperatures exceeding approximately 400° *C. were necessary to produce the relative strengths of the crystals and crystal boundaries required for their formation.*

Even at overheating temperatures of the order of 1400° *C., no incipient fusion was detected at the grain boundaries or within the grains, though there were signs of a metallographic change apparently taking place in the solid state at the grain boundaries and also originating from non-metallic nuclei within the grains.*

It is not unusual for mechanical-test results from forgings of carbon and alloy steels satisfactorily to fulfil the test requirements called for in the specification, although the fractured test-piece discloses small areas of a greyish-coloured, granular faceted nature which have been regarded as evidence that the steel has been "burnt". Another view is that this feature is indicative of overheating before forging or other hot manipulative operations. The original conception of a burnt structure envisaged the granular fracture as the result either of the aggregation of non-metallic particles, with or without oxides, at the austenitic grain boundaries, or of incipient fusion producing grain-boundary membranes. A considerable amount of evidence has accumulated, however, which shows that a repetition of the normal oil-hardening and tempering treatment, or slow cooling from customary forging temperatures, appreciably reduces, and in many cases entirely eliminates, this abnormal type of fracture. It seems logical to conclude, therefore, that had the steel really been burnt, this apparent recovery could not have taken place, and it appeared desirable to carry out an investigation to attempt to ascertain why certain heat-treatment operations apparently produce greater strength in the interior of the crystals than at their boundaries.

Experimental.

Several different heat-treatments were applied to samples machined from nickel–chromium–molybdenum–vanadium steel, the object being to obtain evidence which might assist in determining the temperatures required to give evidence of overheating, and also to produce what has generally been referred to as a burnt fracture; and to produce any technical evidence which might throw light on the cause of this type of fracture. The steel used for the experiments

* Received February 1, 1946. This paper is published by authority of the Alloy Steels Research Committee. The views expressed in it are the author's, and are not necessarily endorsed by the Committee as a body.

was made in the basic electric furnace and had the following chemical composition :

Carbon	0·34%	Nickel	3·46%
Silicon	0·275%	Chromium	0·62%
Sulphur	0·008%	Vanadium	0·07%
Phosphorus	0·012%	Molybdenum	0·53%
Manganese	0·48%		

Overheating temperatures of 1250°, 1300°, 1350°, and 1400° C. were adopted. Some of the samples were cooled relatively slowly in asbestos fibre from the overheating temperatures; others were cooled slowly in asbestos to 850° C. and oil-quenched from that temperature, whilst further samples were oil-quenched from the overheating temperature. Samples which had undergone each of the foregoing treatments were reheated, hardened from 850° C., and tempered at various temperatures up to 650° C. All the specimens were nicked and fractured after their particular heat-treatment, and subsequently examined in the polished and the polished and etched conditions at magnifications up to 1000 diameters. Various etching reagents were tried, including ammonium persulphate and electrolytic etching in ammonium nitrate, but as these reagents did not give consistently satisfactory results, the general examination of microstructures was carried out on specimens etched in either 2% nitric acid in alcohol or 10% nitric acid + 10% sulphuric acid in water.

During the experiments it became evident that the type of fracture obtained was controlled to a great extent by the rate of cooling from the overheating temperature, and also that it was appreciably influenced by subsequent reheating to a normal hardening temperature, and by the subsequent tempering temperature.

The fractures obtained could, in general, be classified under five different types, as depicted in Fig. 1, and subsequently referred to as fractures *A*, *B*, *C*, *D*, and *E*.

Classification of Fractures.

(1) *Fracture* A (*Completely fibrous*).—The specimens showing this type of fracture were subjected to the two following heat-treatment processes :

(*a*) Overheated at temperatures up to 1300° C., cooled in asbestos to 20° C.; reheated to 850° C., oil-quenched, tempered at 650° C., and air-cooled.

(*b*) Overheated at temperatures up to 1350° C., oil-quenched, reheated to 850° C., oil-quenched, and then tempered at 650° C.

In each case metallographic examination showed that the general structure was mainly fine-grained, with no marked boundaries, but with occasional traces of the coarse-grained structure produced by the overheating treatment. Figs. 2 and 3 show typical microstructures of this type of fracture; the samples had been heat-treated as in (*a*) above.

(2) *Fracture* B (*Silky, transcrystalline, the grain boundaries having a somewhat diffused appearance*).—Silky transcrystalline fractures resulted from overheating in the range 1250–1400° C. followed by cooling in asbestos to 20° C.

(*a*) Fig. 4 shows a typical microstructure obtained on specimens overheated to temperatures up to 1350° C.; in each case a coarse-grained structure was apparent, the grain boundaries being indeterminate except where they were partially defined by changes in orientation of the constituents of the individual grains. Naturally the grain-size coarsened as the overheating temperature was raised.

(*b*) On overheating at 1400° C. the microstructure was different. Reference to Fig. 6 shows that when etched in 2% nitric acid the structure consisted of coarse grains with pools of a white-etching constituent (many having minute non-metallic nuclei) within the grains, together with broad white-etching bands along the grain boundaries. These white areas were attacked by the nitric acid reagent (Fig. 7). However, they had no sharply marked outline such as would be expected if incipient fusion had occurred, though their appearance suggested that a phase change might be taking place in the solid state. Fig. 5 shows the typical appearance of these white zones at a magnification of 800 diameters.

(3) *Fracture* C (*Well-defined transcrystalline facets, often showing marked twinning*).—This fracture was obtained by using an overheating temperature of 1250–1400° C., cooling in asbestos to 850° C., and oil-quenching from 850° C.

The microstructures, when etched, were generally very similar to those subsequently described in (*a*) of section (5) on fracture *E*, the coarseness of the grains increasing with the higher overheating temperatures. The actual fractures obtained after heat-treating as in section 5 (*a*) on fracture *E* were of a granular faceted type which persisted after tempering at 650° C., but there appeared to be no metallographic evidence to indicate why the fractures obtained on the heat-treatments given under fracture *C* should be transcrystalline, whilst those obtained with the heat-treatment recorded under (*a*) of fracture *E* should be intercrystalline.

(4) *Fracture* D (*Granular, with bright intercrystalline facets*).—The general procedure for obtaining a structure of this type was to oil-quench from 1250–1400° C., without subsequently oil-hardening from 850° C. and tempering (*cf.* section (5) below.)

The typical metallographic structure is shown by Fig. 12 which represents overheating tem-

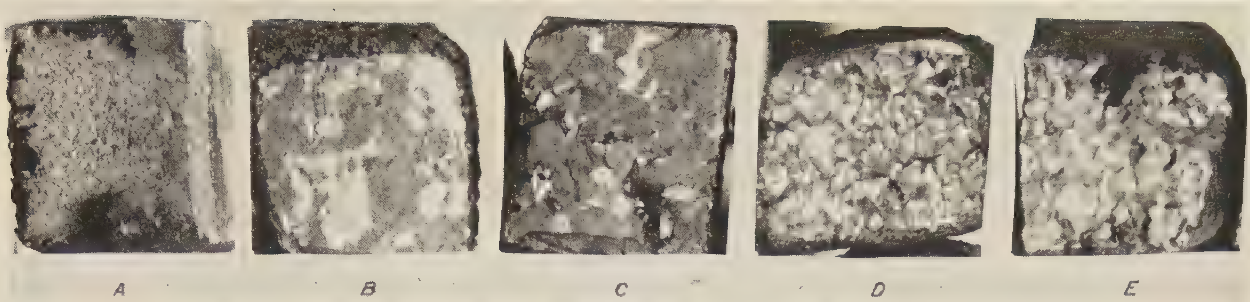


FIG. 1.—Types of Fractures: *A* completely fibrous; *B* silky transcrystalline; *C* well-defined transcrystalline facets, showing twinning; *D* granular, with bright intercrystalline facets; *E* granular, with dull grey intercrystalline facets.

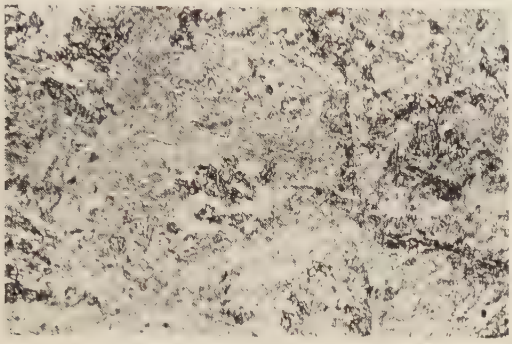


FIG. 2.—Etched with 2% HNO_3.

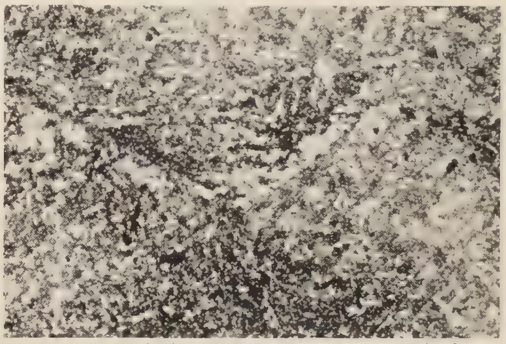


FIG. 3.—Etched with 10% HNO_3 + 10% H_2SO_4.

FIGS. 2 and 3.—Completely Fibrous Fracture. × 100.

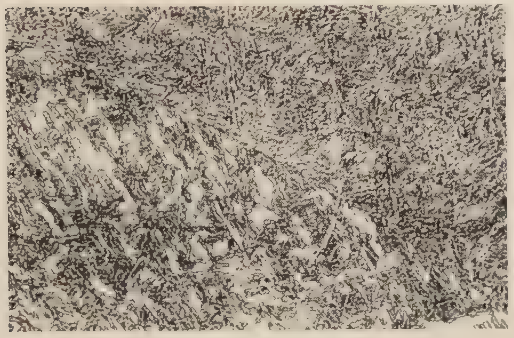


FIG. 4.—Silky Transcrystalline Fracture. Etched with 2% HNO_3. × 100.

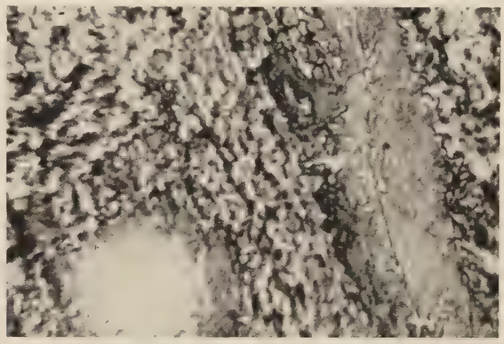


FIG. 5.—Typical Appearance of the White Zones Shown in Fig. 6. Etched with 2% HNO_3. × 800.

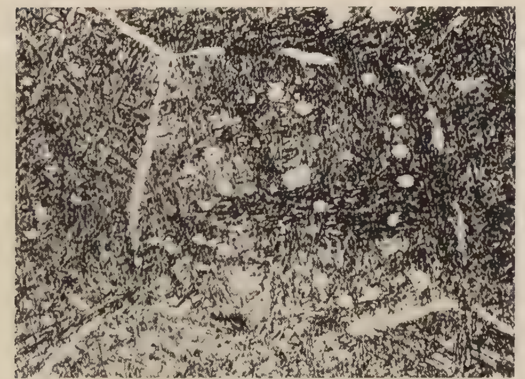


FIG. 6.—Etched with 2% HNO_3.

FIG. 7.—Etched with 10% HNO_3 + 10% H_2SO_4.

FIGS. 6 and 7.—Samples Overheated to 1400° C. × 100.

Micrographs reduced to four-fifths linear in reproduction.

[*Goodrich.*

[*To face p.* 256 P.

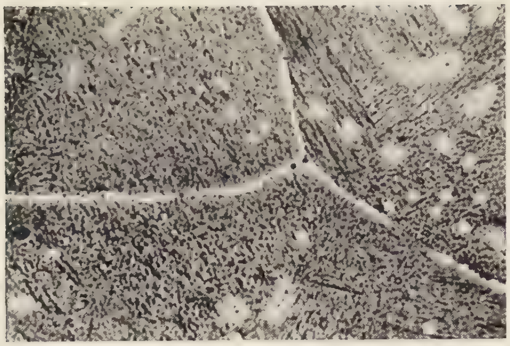


FIG. 8.—× 100.

FIG. 9.—× 800.

FIGS. 8 and 9.—Specimen Oil-Quenched from 1400° C., showing white pools and bands after etching with 2% HNO_3.

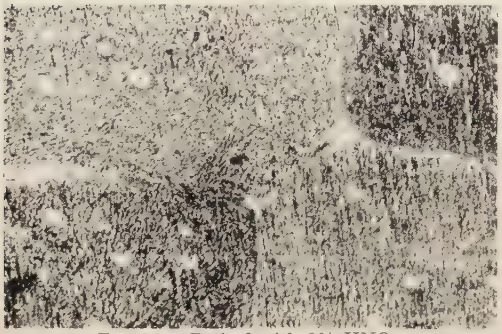


FIG. 10.—Etched with 2% HNO_3.

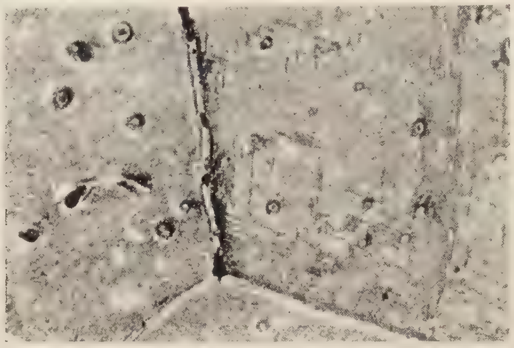


FIG. 11.—Etched with 10% HNO_3 + 10% H_2SO_4.

FIGS. 10 and 11.—Specimen Overheated to 1400° C., showing clearly defined grain boundaries. × 100.

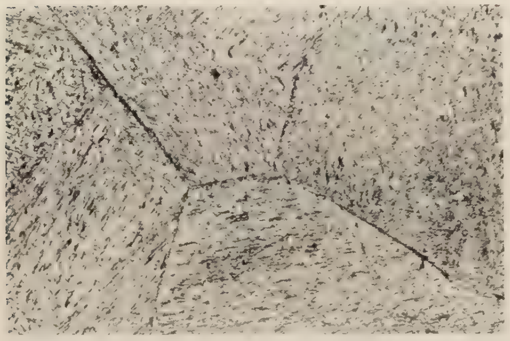


FIG. 12.—Specimen Oil-Quenched from 1300° C., showing clearly defined grain boundaries, Etched with 2% HNO_3. ×. 100.

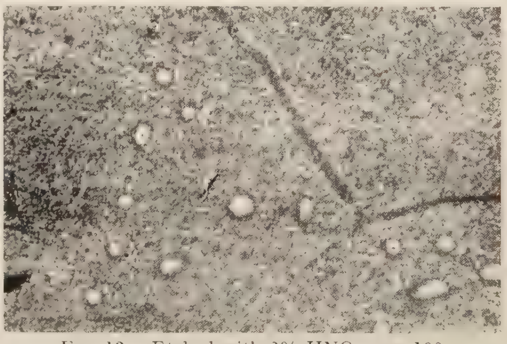


FIG. 13.—Etched with 2% HNO_3. × 100.

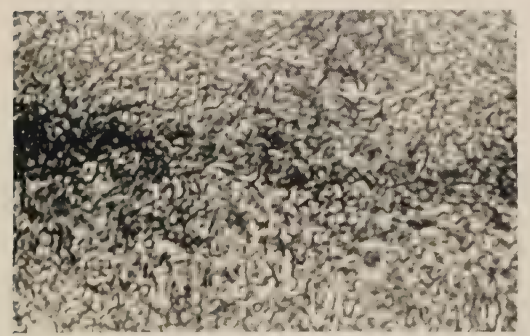


FIG. 14.—Etched with 2% HNO_3. × 800.

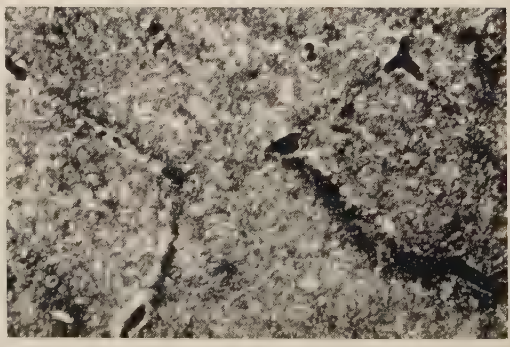


FIG. 15.—Etched with 10% HNO_3 + 10% H_2SO_4. × 100.

FIGS. 13, 14, and 15.—Specimen Overheated to 1400° C., and oil-quenched and tempered after cooling in asbestos, showing dark-etching bands.

Micrographs reduced to four-fifths linear in reproduction.

[*Goodrich.*

[*To face p.* 257 P.

peratures up to 1350° C. The grain boundaries were clearly defined by changes in orientation within the individual grains, but not by any precipitation of metallographic constituents.

An overheating temperature of 1400° C. produced a structure very similar to that obtained with slow cooling in asbestos from 1400° C., with the exception that when etched with 2% nitric acid the white pools within the grains were less numerous, and the white bands at the grain boundaries were narrower. These structures are illustrated in Fig. 8 (at 100 diameters) and Fig. 9 (at 800 diameters). They again suggest that no incipient fusion has taken place.

(5) *Fracture* E (*Granular, with dull grey intercrystalline facets*).—Several treatments were used to obtain this fracture, the overheating temperature being in the range 1300–1400° C.

(*a*) Overheated to 1300–1400° C., slowly cooled in asbestos to 850° C., oil-quenched from 850° C., followed by tempering at 650° C. and cooling in air. The structures formed from the above treatment (with the overheating temperatures in the range 1300–1350° C.) were similar to that shown in Fig. 12. The coarse grain boundaries were clearly defined by changes in orientation within the grains when etched with 2% nitric acid, and by lines of attenuated pits when etched with 10% nitric acid + 10% sulphuric acid. The grain boundaries appeared to be more marked with the higher overheating temperatures.

With an overheating temperature of 1400° C., however, a coarse-grained structure was produced (Figs. 10 and 11) very similar to that obtained on the specimens slowly cooled in asbestos, except that the white-etching bands on the grain boundaries were far less frequent, and in many places were partially transformed into broad, dark-etching contours when etched with nitric acid. No incipient fusion appeared to have taken place either at the grain boundaries or within the crystals.

(*b*) Overheated to 1350° C., cooled in asbestos to atmospheric temperature, followed by oil-quenching from 850° C., and tempering at 650° C. After this treatment the microstructures were very similar to those obtained on specimens heat-treated as in (*a*), except that the presence of some coarse-grained boundaries was more marked.

(*c*) Overheated to 1400° C., followed by cooling slowly in asbestos to atmospheric temperature, or oil-quenching to atmospheric temperature, in each case followed by oil-hardening from 850° C. and tempering at 650° C.

The microstructures obtained on specimens subjected to either of these heat-treatments are, in general, illustrated by Figs. 13, 14, and 15.

It was noticeable that the white-etching boundaries of the asbestos-cooled specimens (fracture *B*) had been almost completely replaced by dark-etching broad bands which were heavily attacked by the nitric-acid/sulphuric-acid reagent but, as illustrated by the dark-etching zone across the centre of Fig. 14, there was still no evidence of incipient fusion.

The specimens oil-quenched from the overheating temperature of 1400° C. (instead of being cooled in asbestos), followed by normal oil-hardening and tempering, showed less numerous white-etching pools within the grains, and there was a comparatively greater prevalence of the broad dark-etching boundaries when etched in nitric acid, and a correspondingly heavier attack when etched in the nitric-acid/sulphuric-acid reagent.

Effect of Tempering Temperature on Signs of Overheating.

In all the foregoing heat-treatments in which a tempering operation was applied, the temperature adopted was 650° C.

Another series of samples (in duplicate) were heated to 1300° C., soaked for 2 hr., cooled slowly in asbestos to 850° C., and oil-quenched. One pair of samples was tempered for 4 hr. at each of the following temperatures: 200°, 400°, 500°, 600°, and 650° C. The samples were then air-cooled. After tempering, one of each pair of samples was fractured, whilst the other was again oil-hardened from 850° C. and again tempered at its original tempering temperature. These samples were then also fractured. A description of the fractures is recorded in Table I.

TABLE I.—*Types of Fractures Obtained after Hardening and Tempering at Various Temperatures.*

Tempering Temp., ° C.	Description of Fracture.	
	After First Hardening and Tempering.	After Second Hardening and Tempering.
None	Fine, well-defined transcrystalline facets.	Fibrous.
200	Semi-fibrous.	Fibrous.
400	Partly dull grey transcrystalline facets. Partly bright granular.	Fibrous, with a few granular intercrystalline facets.
500	Partly bright and partly dull granular facets.	Fibrous, with a few granular intercrystalline facets.
600	Dull granular facets.	Fibrous, with a few granular intercrystalline facets.
650	Dull granular facets.	Fibrous, with a few granular intercrystalline facets.

This portion of the investigation showed very clearly that, after oil-hardening, the tempering temperature adopted had a controlling influence over the formation of the granular intercrystalline facets, and, furthermore, that a repetition of the

normal oil-hardening and tempering treatments was an important factor in their elimination or reduction, both numerically and in magnitude.

Summary and Conclusion.

Some observations resulting from the investigation may be briefly summarized as follows :

(1) Comparatively rapid cooling through the upper critical range is necessary to produce the granular type of fracture.

(2) The granular fracture obtained in specimens heated up to 1350° C. can be partially, if not entirely, obliterated by one or more normal oil-hardening and tempering operations. Repetition of such normal oil-hardening and tempering operations effects a further reduction or obliteration of the granular characteristics.

(3) After oil-hardening from 850° C., an original granular fracture produced by overheating temperatures up to 1350° C. does not reappear on tempering below about 400° C., but does reappear to a lesser degree when tempered between 400° and 650° C. In other words, the tempering temperature after oil-quenching has a markedly controlling influence on the nature of the fracture, the higher temperatures (approximately 400–650° C.) progressively increasing the granular characteristics.

(4) The fact that this granular fracture is not produced unless the material is rapidly cooled through the upper critical range, and that it is also markedly affected by the subsequent tempering temperature, suggests that it is chiefly associated with the relative strength of the crystals and the crystal boundaries. No correlated metallographic change was observed unless the overheating temperature exceeded 1350° C.

(5) For overheating temperatures up to and including 1350° C., the granular fracture is usually indicated by the presence of marked grain boundaries in microspecimens etched in 2% nitric acid in alcohol. Examination at a magnification of 800 diameters has failed to disclose precipitation of any metallographic constituent, the grain boundaries being outlined by a change in orientation of constituents within the neighbouring grains.

(6) Overheating temperatures exceeding 1350° C. produce metallographic changes consisting of white-etching zones on the grain boundaries and white-etching pools within the grains when etched with 2% nitric acid in alcohol. The white-etching zones within the grains usually have a non-metallic nucleus. In the case of material subjected to a hardening and tempering operation after the overheating treatment, these white-etching areas frequently give place, either wholly or in part, to dark-etching zones, but examination at a high magnification failed to produce any evidence of local incipient fusion. This type of structure, however, gives rise to a granular fracture which does not appear to be eradicated by subsequent heat-treatment operations.

Whilst no conclusive metallographic evidence has been forthcoming regarding the fundamental reasons for the different types of fractures encountered in this investigation, it is clear that signs of overheating in steels may be masked by slow rates of cooling and, on the other hand, evidence of overheating may occur in material that is not, in fact, overheated.

It is hoped that the experimental evidence recorded in this paper will at least stimulate discussion regarding the possible physical or metallographic reasons for the relative strength of crystals and crystal boundaries produced by the various heat-treatment operations applied.

Acknowledgment.

The author has pleasure in acknowledging the assistance of Mr. J. Thomson, B.Sc., who carried out a great portion of the experimental work described.

[This paper was discussed jointly with the preceding two by H. J. Merchant on "Some Aspects of the Overheating of Steel Drop-Forgings," by A. Preece, A. Hartley, S. E. Mayer, and J. Nutting on "The Overheating and Burning of Steel," and the following two by F. C. Thompson and L. R. Stanton on "The Effect of Oxygen on the Isothermal Transformations of Steel, and a Suggested Test for Burning," and by J. Woolman and H. W. Kirkby on "Some Experiments on Overheating."]

THE EFFECT OF OXYGEN ON THE ISOTHERMAL TRANSFORMATIONS OF STEEL, AND A SUGGESTED TEST FOR BURNING.*

By F. C. THOMPSON, D.Met., M.Sc., and L. R. STANTON, Ph.D., M.Sc. (University of Manchester).

(Figs. 3 to 14 = Plates XVIII. and XIX.)

Paper No. 19/1946 *of the Alloy Steels Research Committee.*

Synopsis.

Samples of a series of plain carbon steels have been locally burnt, and subsequently isothermally quenched to various temperatures, with a view to finding a test for burnt material.

The results show that certain steels are rendered more reactive by burning, and this suggests a displacement of the inherent **S** *curve; the nature of the final product of transformation indicates that this displacement is in a vertical direction, which in effect acts as a shift to the left.*

The deduction is made that this behaviour is due to the introduction of oxygen during burning, which probably acts indirectly.

The effect is absent in other steels of similar composition, as determined by ordinary methods of analysis, and in general it is found to be too erratic to offer a universal test for burning.

The authors have previously suggested † that an explanation of the phenomenon of "abnormality" may possibly be found in absorbed oxygen moving, directly or indirectly, the **S** curve of the steel to the left, thus rendering the material more reactive. At the time when this hypothesis was propounded, there was no evidence by which its truth could be confirmed.

An attempt has now been made to provide such evidence by a series of experiments which consisted of burning a small area only of a number of specimens of a steel known to behave normally in its original condition. It has thus been possible to compare the microstructures of the burnt and unburnt areas of the same specimen.

Experimental.

The material used was steel *A* of the earlier work, the composition being:

C, %.	Si, %.	Mn, %.	S, %.	P, %.
0·82	0·23	0·32	0·027	0·011

The samples were 1·0 in. long × 0·3 in. in dia. The burning was effected by fitting the two extremities of the specimen into holes in a pair of mild-steel blocks, as shown in Fig. 1, leaving a short central portion exposed, to which the flame of a very oxidizing oxy-acetylene torch was applied. Heating was continued until the surface began to liquefy, the duration being about ½ min.

By this means a very localized burnt spot was produced in a specimen which elsewhere remained unaffected. Subsequent examination of a section

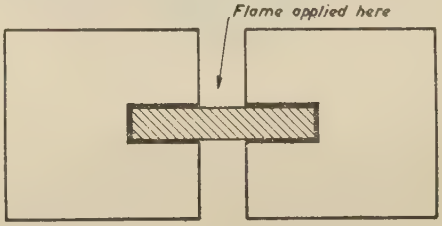


Fig. 1.—Method of Holding the Specimen during Burning.

of the burnt specimen showed that the effect was limited to a roughly conical volume of the sample immediately under the burnt spot.

A flat was then ground on the side of the specimen, as shown in Fig. 2, so that about half the burnt area, surrounded by a considerable region of unaffected material, was exposed. In the subsequent treatment the specimens were heated to the quenching temperature in an atmosphere of dry nitrogen in an electric furnace,

* Received January 31, 1946. This paper is published by authority of the Alloy Steels Research Committee. The views expressed in it are the authors' and are not necessarily endorsed by the Committee as a body.

† F. C. Thompson and L. R. Stanton, *Journal of The Iron and Steel Institute*, 1945, No. I., p. 133 P.

soaked for ½ hr., and then quenched in a bath of low-melting-point alloy maintained at the desired

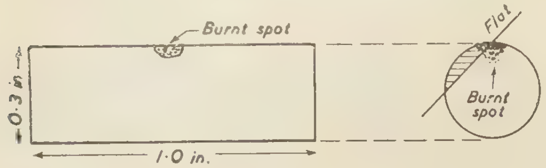


FIG. 2.—Flat Ground on Specimen for Microscopical Examination.

temperature. After immersion in this bath for ½ hr., the specimens were withdrawn and quenched in water.

The extent to which oxidation had occurred during this process may be seen from Fig. 6.

Figs. 3, 4, and 5 show the structures observed in specimens quenched from 850° C. into a bath at 185° C. Fig. 3 shows a region unaffected by the burning, consisting almost entirely of acicular martensite, the light background representing that austenite which had remained unchanged at the time of removal from the bath, and had then transformed to a more or less structureless martensite during the subsequent water-cooling. Fig. 4 shows the structure found in the marginal region between the burnt and unburnt parts, consisting of much finer martensite needles interspersed with troostite, especially at the boundaries of the original austenite grains. Fig. 5 shows the structure in the burnt portion, in which the transformation to troostite is almost complete. The bath temperature employed corresponded to the line of demarcation between that leading to a transformation entirely to martensite, and that leading to martensite with troostite.

These results show clearly that the tendency to produce troostite has been increased as a result of the burning. The phenomena persisted to some extent at still higher bath temperatures, in that while troostite now appeared in both the burnt and unburnt zones, it appeared in greater quantity in the burnt part.

It is quite clear then that the effect of the burning has been to accelerate the rate of breakdown of the austenite, which is essentially complete in the burnt region, as compared with less than 50% elsewhere, whilst, in addition, the final product is not the same. That the presence of oxygen—directly or indirectly—does make steel more reactive, *i.e.*, it moves the **S** curve to the left, so far as this steel is concerned, also seems clear.

There is, however, the possibility to be considered that the change in the rate of decomposition of the austenite may be caused by the loss of carbon resulting from the burning treatment. To determine the extent to which such decarburization has occurred, a similar locally burnt sample was heated to a temperature of 850° C. and furnace-cooled. Fig. 7 shows the structure of the burnt part, and Fig. 8 that of the normal zone after this treatment. It will be seen that both are representative of a slightly hypo-eutectoid steel, and that in the region examined the loss of carbon during the short time for which the steel was burnt cannot have been very serious.

The effect of the possible loss of carbon was further examined by subjecting to the same heat-treatment a normal, unburnt sample of a steel similar in composition to steel *A*, except that it contained only 0·6% of carbon. Although the carbon content in this case was distinctly lower than that of the burnt portion of steel *A*, there was no difficulty in obtaining a structure which consisted of martensite only (Fig. 9). Hence the loss of carbon cannot be the sole cause of the more rapid transformation found in the burnt samples.

We are left, therefore, with the oxygen introduced during burning as being, directly or indirectly, the cause of the difference in the isothermal transformation of the burnt and unburnt parts. In other words, oxygen, directly or indirectly, moves the **S** curve to the left.

The validity of our initial assumption having been established, it becomes of considerable interest to see how far such isothermal behaviour can be employed as a test of burning, and it is with this that the rest of the paper is mainly concerned.

RATE OF ISOTHERMAL TRANSFORMATION AS A TEST OF BURNING.

So far, the burning effect has been revealed only in the case of steel *A*. Experiments of a similar character were next made on a range of steels of varying carbon content, and also on another steel, *P*, of approximately eutectoid composition. The carbon contents of these steels were as follows:

Steel:	*B.*	*C.*	*D.*	*E.*	*P.*
Carbon, % . .	0·15	0·50	1·20	1·70	0·78

In order to select the temperature of the bath in which these steels were to be quenched, a series of experiments was made with each steel to find the temperature below which the product of transformation (for the size of specimen employed) was entirely martensite, and above which troostite appeared. For these experiments the bath temperatures chosen were therefore a few degrees below this boundary, as follows:

Steel:	*B.*	*C.*	*D.*	*E.*
Bath temp., ° C. .	270	300	300	250

Samples which had been burnt in the manner already described were then heated in nitrogen

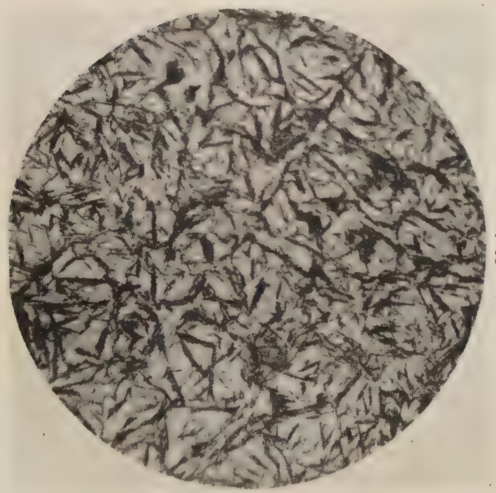


FIG. 3.—Unburnt area.

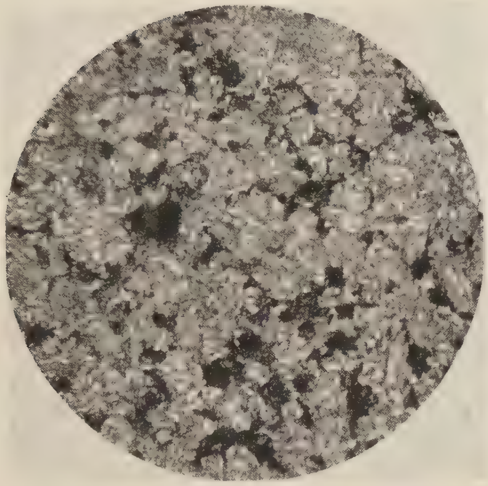


FIG. 4.—Marginal area between burnt and unburnt zones.

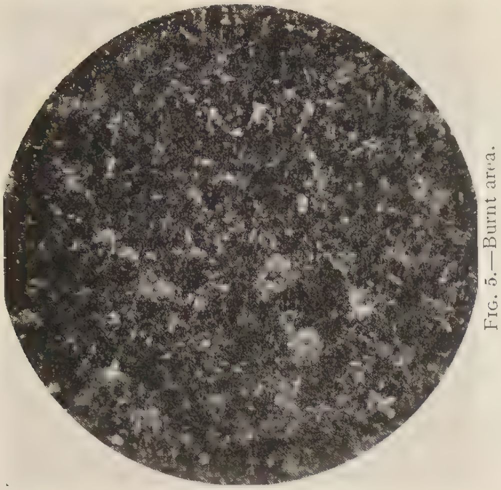


FIG. 5.—Burnt area.

FIGS. 3 to 5.—Steel *A* after Isothermal Treatment at 185° C. × 270.

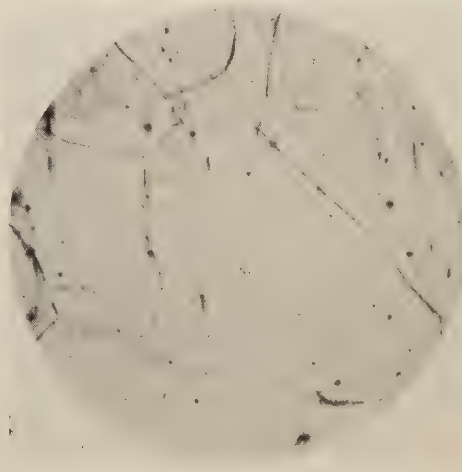


FIG. 6.—Burnt Area before Etching; oxide particles in grains and along boundaries. × 120.

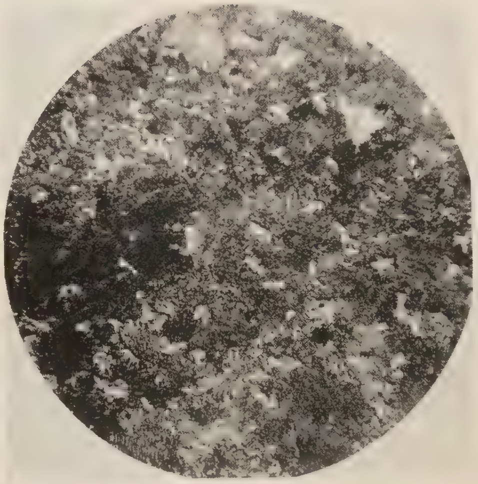


FIG. 7.—Burnt area.

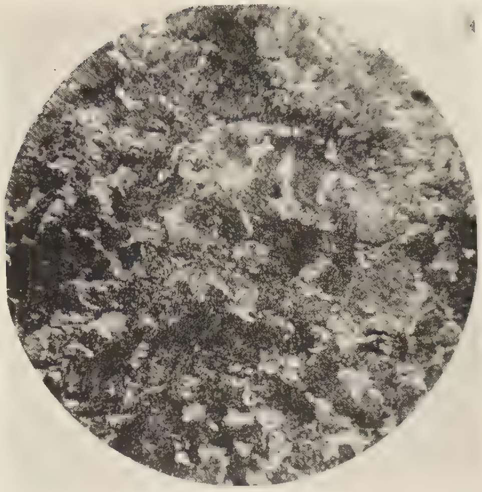


FIG. 8.—Unburnt area.

FIGS. 7 and 8.—Pearlite Formed in Steel *A* during Furnace Cooling from 850° C. × 240.

[*Thompson and Stanton.*

[*To face p.* 260 P.

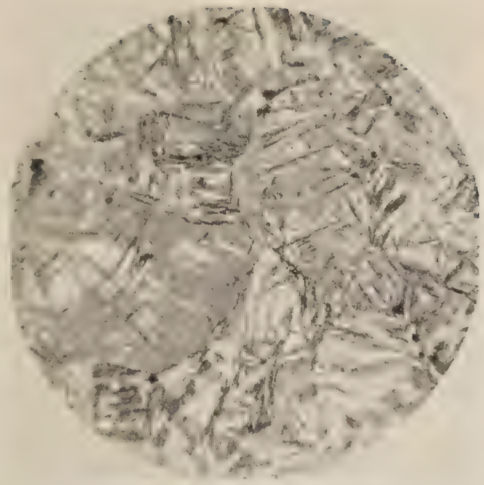


FIG. 9.—Martensite Formed by Isothermal Treatment of 0·6% Carbon Steel at 185° C. × 240.

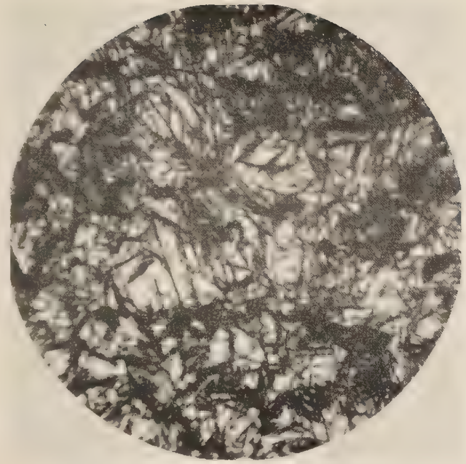


FIG. 10.—Burnt area: fine martensite.

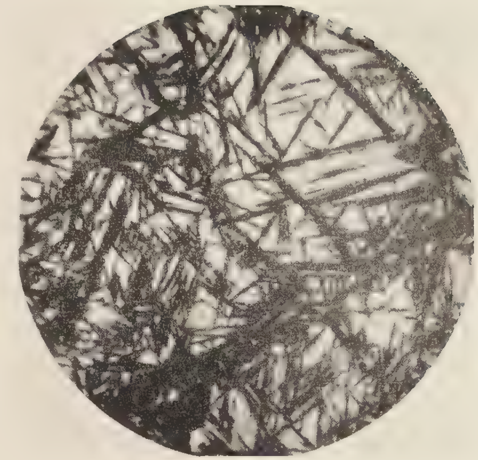


FIG. 11.—Unburnt area: coarse martensite.

FIGS. 10 and 11.—Steel *A* after Repeated Isothermal Treatments at 185° C. × 360.

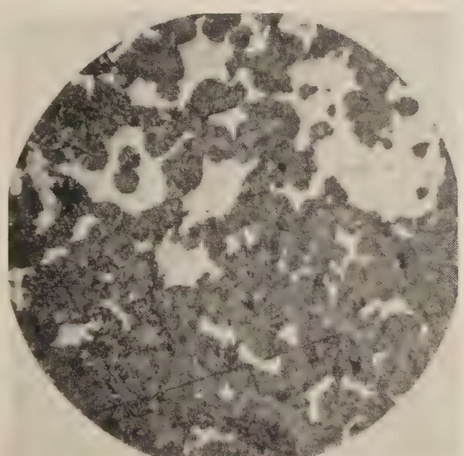


FIG. 12.—Outer part of section.

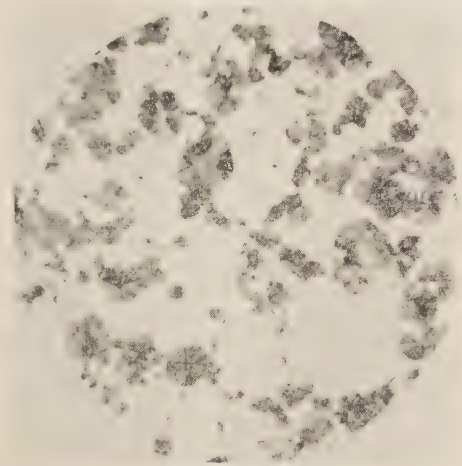


FIG. 13.—Centre of section.

FIGS. 12 and 13.—Variation in Quantity of Troostite across a Section of Steel *A*. × 125.

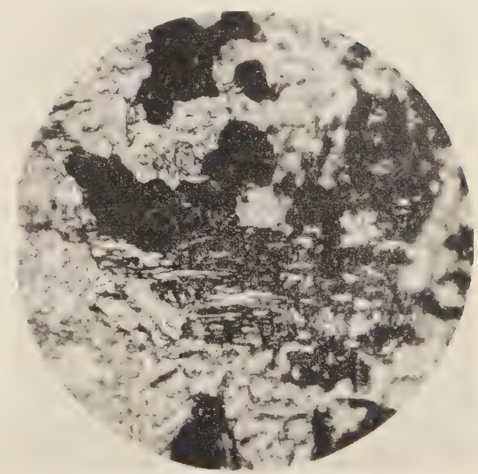


FIG. 14.—Troostite associated with slaggy inclusion in core of a case-hardened sample. × 900.

[*Thompson and Stanton.*

[*To face p.* 261 P.

to a temperature (depending on the carbon content) high enough to render them completely austenitic, and quenched in a bath at the appropriate temperature.

Microscopical examination revealed the perplexing fact that no effect of burning was to be observed, even when burning was sufficiently drastic to reduce the cross-section by half. On repeating the experiments with a slightly higher bath temperature, nodular troostite was found in the normal way.

Experiments were then made with the eutectoid steel *P*; this was found to be somewhat less reactive than steel *A*, but, in this case also, examination after the isothermal treatment failed to show any difference between the two zones. However, when this steel was burnt very severely, subsequent examination showed that, though the structure in both the burnt and unburnt zones was martensitic, the martensite in the burnt area etched noticeably darker than that elsewhere. This may indicate that the decomposition of the austenite had proceeded further in the burnt material, *i.e.*, that this too was more reactive.

It may be concluded that, while burning may alter quite definitely the manner in which the austenite decomposes, the effect varies enormously from steel to steel.

Returning the steel *A*, a spot-burnt sample was subjected to several successive isothermal treatments to ascertain whether the effect was permanent. Examination of such a specimen quenched repeatedly from 850° C. into a bath at 185° C. and kept there for 30 min., showed that the preferential formation of troostite in the burnt zone was gradually eliminated, so that none occurred after five such treatments. There was again, however, a slight difference in the types of martensite in the two areas, which is clearly shown in Figs. 10 and 11. Fig. 10, from the burnt zone, shows that the amount of austenite transformed is greater than that in the unburnt region (Fig. 11) and further, that the needles are distinctly smaller in the former case than in the latter. The experiment was repeated a sixth time, but with the bath temperature somewhat raised (280° C.); troostite again appeared in the burnt zone, and martensite alone in the normal regions.

These observations are of considerable interest and importance in showing that the effects of burning are not confined to the grain boundaries, but penetrate to the very centres of the grains.

It would appear, therefore, that the continued heat-treatment resulted in the gradual elimination of some condition affecting the burnt zone by diffusion or by a reaction with some other element present. On the other hand, the result of the sixth treatment above seems to show that the burnt condition still prevails when the temperature of the austenite decomposition occurs in a range which is more favourable for the formation of troostite.

In the course of the experiments it was observed that when a normal specimen was quenched from 950° C. into the bath at 500° C., there was some difference in the proportions of troostite and martensite across the section, troostite being noticeably preponderant at the edges. This can be seen by comparing Fig. 12 (a section near the edge) with Fig. 13 (a section nearer the centre). The difference in structure may be explained on the grounds of superficial oxidation, which may have occurred in spite of the nitrogen atmosphere, or it may be correlated with the similar effects, already reported by the authors, in which the formation of martensite occurs first at the surfaces.

As confirmation of the general thesis that oxygen makes a steel more reactive, the structure in the core of a case-hardened steel which contained a very large amount of included matter may be mentioned.

The normal structure of ferrite and martensite occupied the major portion of the field, but dotted about in this were much darker, isolated regions. At higher magnification these regions were revealed as troostitic or pearlitic areas embedded in ferrite (Fig. 14), and in each of them was a clearly defined inclusion of slaggy matter. It is impossible to escape from the view that the change of structure was due to the latter, a view completely concordant with the hypothesis that the higher oxygen content in such regions had accelerated the rate at which the austenite had broken down under similar conditions of cooling.

There is evidence for the belief that the presence of gases in steel has an effect on the rate of austenite decomposition. It is of interest, therefore, to ascertain the effect of reducing such gas content on the behaviour of a steel when it is first burnt, and then isothermally transformed.

Two specimens of steel *A* were annealed *in vacuo* at a temperature of 600° C. for 6 hr., under a pressure of about 0·3 mm. of mercury. The heating was not commenced until there was a satisfactory vacuum, and this was maintained until the cooling was completed. The specimens were then spot-burnt under conditions similar to those already described, after which they were heated in nitrogen to 850° C. and quenched in the metal bath at 185° C.

Microscopical examination failed to reveal any difference whatever between the burnt and unburnt regions. Two other specimens of the same steel were first burnt and then vacuum-annealed, again at 600° C. for 6 hr. On isothermally transforming the samples quenched from 850° C. into a bath at 185° C., identical structures were obtained in both the burnt and normal zones. Such evidence strongly suggests that the gas content of the steel plays a most important part, and it

Table I.—*Structures of Steel* P *Isothermally Transformed at Various Temperatures.*

Burnt.			Unburnt.		
Bath Temp., ° C.	Time, min.	Structure.	Bath Temp., ° C.	Time, min.	Structure.
265	15	Martensite	296	10	Martensite.
325	15	Martensite.	348	10	Martensite and troostite.
352	10	Martensite.			
398	60	Martensite, with a very little troostite.	396	10	Troostite, with a very little martensite.

goes far to explain the abnormal results that are sometimes obtained in the isothermal treatment of certain steels.

Some results obtained with steel *P*, transformed at higher bath temperatures, may be cited as an example of such anomalous behaviour. These are presented in Table I., and it will at once be apparent that, so far as the higher transformation temperatures are concerned, it is the unburnt material which is the more reactive.

Returning to the specimens which had been subjected to a degassing treatment, control specimens which had not been vacuum-annealed were given an otherwise exactly similar isothermal treatment. The control specimens showed a structure consisting of martensite with nodular troostite, the degassed samples being fully martensitic.

A further point for which there is some evidence is that the rate of change of the austenite, once breaking-down has started, *i.e.*, the distance between the lines for initial and complete transformation, is affected by the burning.

Complex as the evidence is, it is possible to suggest a hypothesis which is, at any rate, consistent with the main outlines. It is propounded in the hope that it will lead to critical discussion, and anything approaching dogmatism is completely unjustified in the present stage of knowledge.

Dealing in the first place with the results obtained on steel *A* at bath temperatures below the peak in the S curve for the normal material, not only has evidence been provided which shows that the curve is moved to the left, but also that there is a difference in the constituents present between the normal and the burnt material. For this it is essential that, not only should the S curve be shifted laterally, but also vertically. Since the burnt steel shows troostite at temperatures at which normal material is fully martensitic, it would appear that the burning must have depressed the peak, as shown in Fig. 15.

If the full lines represent the normal steel and the dotted lines the burnt steel, then at such a point as *A*, the structure of the former should consist of martensite (acicular) formed in the bath, and almost structureless martensite produced from unchanged austenite during the subsequent water-quenching. This is the structure shown in Fig. 3. For the burnt steel, on the other hand, an almost entirely troostitic structure would be expected—the steel was treated at a temperature above the peak of the curve—together with a small amount of martensite formed from the austenite which had not yet transformed. This is shown in Fig. 5.

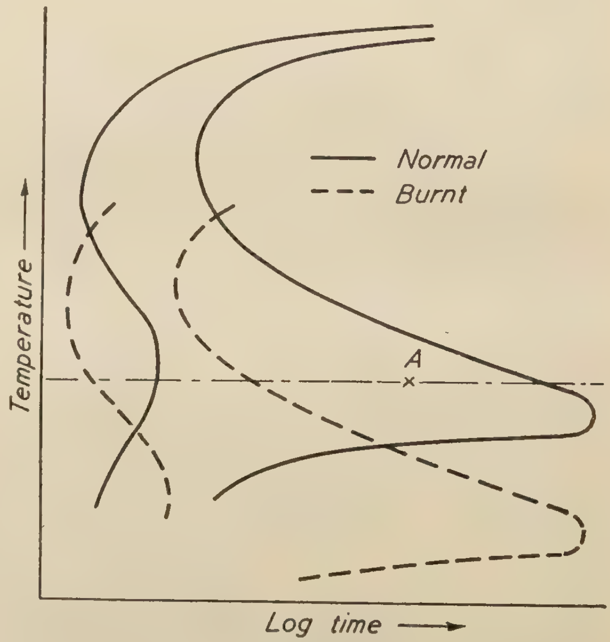


Fig. 15.—Depression of S Curve.

The results obtained on steel *P*, at the higher bath temperatures, cannot, so far as we can see, be explained on the basis of this hypothesis, and in this case an explanation of the structures can be obtained only if the curve is *raised*. In Fig. 16, this suggestion is shown diagrammatically. In area *A*, the burnt sample will have undergone no transformation and on cooling will pass over to martensite, whilst the normal steel will show a structure consisting of martensite (formed during the cooling), together with troostite produced in the bath. This, as will be seen from Table I., is what did occur in the higher temperature range. In area *B*, the normal steel will be fully troostitic, and the burnt steel will consist of troostite and martensite.

Now, it will be obvious, at any rate in two steels as similar in composition as are steels *A* and *P*, that oxygen cannot *directly* both raise and lower the peak in the S curve at the same time.

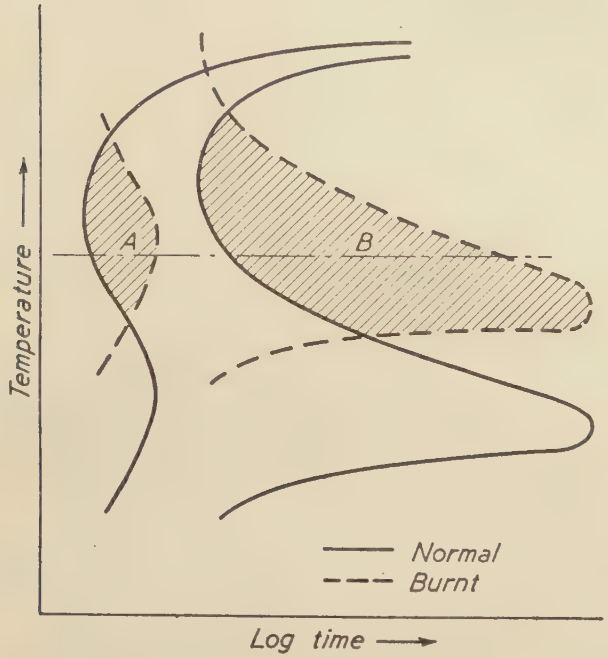


Fig. 16.—Elevation of S Curve.

It follows, therefore, that the oxygen taken up during burning must exert its influence indirectly through some other constituent of the steel. The oxidation of manganese would have this effect so far as the lateral movement of the curve is concerned, and this may play its part. The results obtained on the degassed samples, however, point very strongly to the view that the changes produced by the burning are, in considerable measure, due to changes in the content of gases in the steel. Since different supplies of the same steel would vary in this respect, this would explain the erratic results obtained from time to time in the isothermal treatment of steels, especially of the rapidly reacting, plain carbon steels.

Summary of Results.

(1) The rate of breakdown of austenite may be accelerated by burning.

(2) The presence of oxygen, directly or indirectly, makes the steel more reactive, *i.e.*, it moves the S curve to the left.

(3) Since decarburization during burning is only slight, it cannot be the sole cause of the more rapid transformation found in the burnt areas.

(4) When the product of the decomposition is martensite, the effects of burning are not confined to the grain boundaries, but penetrate to the centre of the grains.

(5) The rate of austenitic decomposition is affected by the presence of gases in the material.

Conclusion.

It will be seen from the foregoing that although in some material it is possible to differentiate quite clearly between the normal and burnt states, it is, at the moment, quite impossible to suggest any test based on isothermal behaviour which can have general applicability.

Acknowledgments.

The authors' thanks are due to the Alloy Steels Research Committee for financial aid ; to Mr. P. C. Ho, Mr. F. Sharp, B.Sc., and Mr. M. D. Jepson, B.Sc., who assisted in the experimental work; and especially to Mr. W. Ashelby, Steward of the Metallurgy Department, for help at all times.

[This paper was discussed jointly with the preceding three by H. J. Merchant on "Some Aspects of the Overheating of Steel Drop-Forgings," by A. Preece, A. Hartley, S. E. Mayer, and J. Nutting on "The Overheating and Burning of Steel," and by W. E. Goodrich on "Overheating and Burning of Nickel–Chromium–Molybdenum Steel" and the following one by J. Woolman and H. W. Kirkby on "Some Experiments on Overheating."]

SOME EXPERIMENTS ON OVERHEATING.*

By J. WOOLMAN, M.Sc., and H. W. KIRKBY, Assoc.Met. (The Brown-Firth Research Laboratories, Sheffield).

(Figs. 1 and 2 = Plate XX.)

Paper No. 21/1946 of the Alloy Steels Research Committee.

A series of experiments have been carried out which were designed to throw light on the phenomenon of overheating and the factors affecting it. Some evidence is submitted in support of a hypothesis that the overheating phenomenon indicated by faceted fractures is a precipitation effect and is not the result of external gas atmospheres. It is considered that the precipitate is already present in the steel as cast, and the effect of heating to a high temperature is to redissolve it. Subsequent cooling, if at a suitable rate, results in a precipitate forming at the existing austenite boundaries which then persists as a network. This is reflected in the final fracture test by interruptions in the path of the crack, giving rise to the faceted type of fracture.

The indications are that the rate of cooling from the overheating temperature is an important factor in producing faceted fractures. The method of steelmaking and the addition of aluminium and other killing agents also have an influence on the minimum overheating temperature, although the reasons for both effects are not yet clear.

The vacuum-melting experiments have also shown that remelting a material having a very high minimum overheating temperature can substantially reduce that temperature, although the variables due to changes in composition introduce complexities.

Besides oxygen, the sulphur contents appear to play an important rôle in the phenomenon.

Introduction.

The work reported in this paper was initiated by the finding of overheating effects, namely, faceted fractures, in certain forgings made from 3% nickel–chromium–molybdenum, 3% nickel–chromium–molybdenum–vanadium, and 2/2 nickel–chromium steels. Preliminary work consisted in evaluating the overheating temperatures for the different steels, attempts to recover overheated material, and the determination of factors affecting the response of the steel to exposure at high temperatures. As a result of these preliminary experiments further work has been carried out, particularly to ascertain what factors in the steelmaking conditions have an influence on the overheating temperature, since considerable confirmatory evidence had been obtained that the overheating temperature tends to be different in steels made by different processes.

Various preliminary experiments were carried out on the following subjects :

(1) The effect of heat-treatment on material showing facets.

(2) The effect of rate of cooling from the overheating temperature.

(3) Determination of minimum overheating temperature.

(4) The effect of furnace atmosphere on the formation of facets.

(5) The effect of forging on overheated steel.

(6) Discussion of results arising out of experiments (1) to (5).

Subsequent work was designed to throw light on the hypotheses arising from the earlier work listed above. The further experiments consisted of :

(7) Examination of 3% nickel–chromium–molybdenum ingot material (*i.e.*, without forging).

(8) The effect of further heat-treatment on material quickly cooled from the overheating temperature.

(9) The effect of the method of steelmaking on the minimum overheating temperature.

(10) The effect of aluminium additions on the minimum overheating temperature.

(11) Vacuum-melting experiments.

Definition of Overheating.

It is necessary at this stage to define the term "overheating," and the method used for its

* Received February 1, 1946. This paper is published by authority of the Alloy Steels Research Committee. The views expressed in it are the authors' and are not necessarily endorsed by the Committee as a body.

detection as applied to the present work. Thus, the term is used throughout to signify that a material in the overheated condition gives a faceted fracture after being subjected to a normal nicked-fracture test, the material being in a reasonably refined, hardened, and fairly fully tempered condition. Thus the final treatment consisted of normalizing at 950° C., oil-hardening from a temperature depending upon the type of steel, and tempering at 650° C. for 1 hr. All fracture-test results quoted in the present paper refer to samples tested under these conditions.

The definition also covers the presence of heavy coarse networks when refined, hardened, and tempered material is etched with the H_2SO_4/HNO_3 reagent.

Experimental.

(1) *The Effect of Heat-Treatment on Material Showing Facets.*

This series of experiments was confined to a sample from a 3% nickel–chromium–molybdenum–vanadium steel forging of the following composition:

C, %.	Ni, %.	Cr, %.	Mo, %.	V, %.
0·30	3·25	0·70	0·65	0·25

The object was to eliminate facets by commercial heat-treatments. The work was later extended to treatments which would hardly be considered commercial. In all cases the treatments were carried out on material of 1-in. sq. section from one forging which showed a severe degree of overheating as judged by the numerous facets in the fractured test-pieces.

The following treatments were carried out:

(*a*) N. 950° C. ½-hr. and 1-hr. soaking periods.
(*b*) N. 1050° C. ,, ,, ,,
(*c*) N. 1100° C. ,, ,, ,,
(*d*) N. 1150° C. ,, ,, ,,
(*e*) N. 1150° C. + N. 950° C. (1-hr. soaking period in each case).
(*f*) N. 1200° C. + N. 1100° C. + N. 1000° C. (1-hr. soaking period in each case).
(*g*) F.C. 1200° C. (6-hr. soaking period) + N. 950° C. (1-hr. soaking period).
(*h*) F.C. 1250° C. (6-hr. soaking period) + N. 950° C. (1-hr. soaking period).
(*i*) F.C. 1300° C. (6-hr. soaking period) + N. 950° C. (1-hr. soaking period).
(*j*) 1200° C. (1-hr. soaking period) F.C. to 800° C. O.Q.
(*k*) 900° C. (48-hr. soaking period). A.C.

N. = Normalized.
F.C. = Furnace-cooled.

After these treatments all samples were oil-hardened from 850° C. and tempered at 650° C.

None of the treatments was found to have an appreciable influence on the elimination of facets in the fracture.

(2) *The Effect of Rate of Cooling from the Overheating Temperature.*

Two steels were investigated:

	C, %.	Si, %.	Mn, %.	S, %.	P, %.	Ni, %.	Cr, %.	Mo, %.	V, %.
Cast 88609 (3% Ni–Cr–Mo–V Steel):	0·30	0·25	0·65	0·011	0·009	3·29	0·92	0·60	0·24
Cast 95847 (2/2 Ni–Cr Steel):	0·52	0·25	0·10	0·011	0·012	1·99	1·94	...	...

The work leading to the study of the effect of the rate of cooling was concerned initially with attempts to eliminate facets in the nickel–chromium–molybdenum–vanadium steel by heating faceted material in a coal-gas atmosphere. Several erratic and misleading results were obtained, since the factor of rate of cooling was not appreciated at the time. Thus, as a result of this work, it was found that whilst furnace-cooling (at the rates given in Table I.) from a suitable temperature produced faceted fractures, air-cooling a ¾-in. sq. bar from the same temperature resulted in a fracture almost free from facets. Oil-quenching from the same temperature gave a fracture quite free from facets. This effect was also observed with the 2/2 nickel–chromium steel.

With a view to forming some idea of the temperature at which facets were initiated on furnace-cooling, a number of ¾-in. sq. samples of the nickel–chromium–molybdenum–vanadium and the nickel–chromium steels were heated for 1 hr. at 1350° C. in a gas muffle furnace and furnace-cooled. During the cooling, samples were taken out of the furnace at 50° C. intervals and oil-quenched and then given the final normalizing, oil-hardening, and tempering treatments. The results of nicked-fracture examination are given in Table I.

Table I.—*The Effect of Quenching and Cooling Conditions on the Presence of Facets in Fractures.*

Quenching Temp., ° C.	Time to Cool from 1350° to Temp., min.	Appearance of Fracture.	
		Ni–Cr–Mo–V Steel.	Ni–Cr Steel.
1300	2¼	Free from facets.	Free from facets.
1250	4½	Suspicion of facets.	,,
1200	8½	Fine facets.	,,
1150	13	,,	,,
1100	17½	,,	,,
1050	23¼	,,	Large facets.
1000	30½	,,	,,
950	37½	,,	,,
900	45½	,,	,,
800	64½	,,	,,
Room temp.	...	,,	,,

No further work of this type was carried out on the nickel–chromium–molybdenum–vanadium steel, but additional experiments were made in the case of the nickel–chromium material. The suppression of facets with the quenching temperature at 1100° C. and higher in the case of the nickel–chromium steel suggested either a "non-reactive" zone or, alternatively, that the time at these temperatures was not sufficient to produce facets. Therefore, to eliminate one or other possibility, one sample was heated for 1 hr. at 1350° C. and furnace-cooled at the same rate as before to 1150° C., and then again held for 1 hr., and finally oil-quenched. Another sample was similarly treated, but cooled to 1100° C. and held for 1 hr. before oil-quenching. Nicked-fracture tests revealed a few large facets in both samples.

These results suggested that facet formation at these temperatures was a matter of time at the temperature, although the number of facets obtained was not as great as would be expected from an overheating temperature of 1350° C. The reason for this limited number, however, is discussed further in section (8).

As a result of the above work, subsequent overheating experiments were standardized, as regards cooling from the overheating temperature, by furnace-cooling from the reheating temperature to 800° C. followed by air-cooling. This step was taken with a view to accelerating the general programme.

(3) *Determination of Minimum Overheating Temperature.*

Details of the three steels used in these experiments are given below:

	C, %.	Si, %.	Mn, %.	S, %.	P, %.	Ni, %.	Cr, %.	Mo, %.	V, %.
Cast 88123 (3% Ni–Cr–Mo Steel):	0·30	0·28	0·63	0·007	0·010	3·21	0·89	0·66	...
Cast 88767 (3% Ni–Cr–Mo–V Steel):	0·30	0·25	0·62	0·010	0·010	3·27	0·97	0·66	0·25
Cast 95847 (2/2 Ni–Cr Steel):	0·52	0·25	0·10	0·011	0·012	1·99	1·94	...	...

In each case approximately 1-in. sq. bars, cut from larger forgings, were used.

Determinations of minimum overheating temperatures were made in each case, with the following results:

	Min. Overheating Temp., ° C.
3% Ni–Cr–Mo steel	1350–1375
3% Ni–Cr–Mo–V steel	1300–1325
2/2 Ni–Cr steel	1200–1225

Further work was carried out on several more casts of each steel except the nickel–chromium steel, and the above values were confirmed.

In all cases the presence or absence of overheating was determined by the usual two methods: (*a*) The nicked-fracture test, and (*b*) by etching a prepared section in the H_2SO_4/HNO_3 reagent. In general, it could be said that the facet size agreed approximately with the "grain-size" revealed after etching with the H_2SO_4/HNO_3 reagent, although precise determinations were difficult. Where measurements were considered to be reliable there also seemed to be a correlation between the austenitic grain-size formed at the overheating temperature and the "grain-size" revealed by the H_2SO_4/HNO_3 reagent. This aspect of overheating is dealt with more fully in a later section.

(4) *The Effect of Furnace Atmosphere on the Formation of Facets.*

The work in this case was very limited, but was carried out to check the old theory that facet initiation was due to outside influences such as atmosphere. Samples of 2/2 nickel–chromium steel were overheated to temperatures of 1300–1325° C. under each of the following conditions: In (*a*) an electric muffle furnace with an air atmosphere, (*b*) a gas muffle furnace, (*c*) a neutral salt bath, and (*d*) a vacuum furnace (0·001 mm. of mercury). In every case the fractures contained numerous large facets.

It should also be mentioned here that the same work was carried out on an overheated 3% nickel–chromium–molybdenum steel in an atmosphere of coal gas with a view to eliminating facets (*see* section (1)). Samples were heated above the minimum overheating temperature in coal gas, held for 1 hr., and furnace-cooled. Subsequent nicked-fracture tests revealed faceted fractures as severe as those obtained on the original material.

(5) *The Effect of Forging on Overheated 2/2 Nickel–Chromium Steel.*

The object of this experiment was to determine the effect of forging on material heated above the minimum overheating temperature (previously determined as 1200–1225° C.), as regards both response to forging and its effect on the subsequent nicked-fracture test. For this work the same 2/2 nickel–chromium steel was used as in section (3); three samples 6 in. long were forged from $4\frac{1}{2}$ to $3\frac{3}{8}$ in. in dia. over the following temperature ranges:

	Sample *A*. °C.	Sample *B*. °C.	Sample *C*. °C.
Heated to:	1250	1275	1300
Commenced forging: .	1240	1260	1280
Finished forging: . .	1060	1120	1160

Temperature measurements were made on the outside of the bars by an optical pyrometer, and the values quoted should therefore be regarded in the nature of a guide rather than absolute values. All material forged successfully.

All the bars were softened by normalizing at

870° C., tempering at 660–670° C., and furnace-cooling. They were then sectioned longitudinally so that a $\frac{3}{4}$-in. sq. section was obtained from outside and inside positions for subsequent nicked-fracture tests. These were carried out after oil-hardening at 870° C. and tempering at 650° C. for 1 hr., with the following results:

	Appearance of Fracture. Outside.	Inside.
Sample *A*	No facets.	No facets.
Sample *B*	,,	,,
Sample *C*	,,	Very fine facets.

Micro-examination after etching with the H_2SO_4/HNO_3 reagent showed a well-marked network corresponding to an index No. (A.S.T.M.) of 2 in the sample showing evidence of facets, but there was no evidence of overheating in the other cases. In addition, the overheated sample showed evidence of more than one generation of networks (Fig. 1).

"Grain-size" data (measured on the network after etching with the H_2SO_4/HNO_3 reagent) from the laboratory overheating experiments (without forging) carried out on the 2/2 nickel–chromium steel used for the work reported in section (3), are given below:

Overheating Temp., ° C.	Appearance of Fracture,	Grain-Size (A.S.T.M.).
1150	No facets.	2
1200	Suspicion of facets.	1
1225	Facets.	0
1250	,,	−2
1275	,,	−3
1300	,,	−5

As previoulsy mentioned, the facet size increased with increase in temperature.

Consideration of the two sets of data brings out the following points:

(i) Under conditions of heating plus forging, the overheating temperature is apparently raised by approximately 75° C. (or 100° C. if the outside material of the 1300° C. test is considered).

(ii) The very fine facets observed in the centre of the test-piece heated to 1300° C. along with the grain-size of 2 (which roughly approximates to a temperature of 1150° C. for this material) taken in conjunction with the data derived from the laboratory overheating experiments (section (3)) suggest that even this test-piece would not have shown facets had the finishing temperature been a little lower.

(iii) This work explains the apparent overheating observed in certain forgings where a marked feature was the apparent small "grain-size" (approximately 2) of the heavy network revealed by the H_2SO_4/HNO_3 reagent. It also explains the procedure for obtaining several generations of network which was also an effect observed in these forgings. Figs. 1 and 2 illustrate typical networks found on the experimentally forged sample and on a commercial forging, respectively.

(6) *Discussion of Results of the Foregoing Experiments.*

Several interesting points emerge in considering the data from all these experiments:

(*a*) There appears to be a minimum temperature above which facets are initiated.

(*b*) This minimum temperature differs for different steels.

(*c*) Above the minimum temperature the range of facet initiation is fairly wide, the top extreme being considered as visible oxide films at the austenite grain boundaries existing at the temperature in question. (The appearance of definite oxide-film formation is, however, considered to be a different phenomenon.) Thus, the 3% nickel–chromium–molybdenum–vanadium steel shows signs of overheating at 1300–1325° C., becoming very definite at 1350° C., and, as later experiments have shown, more so at 1375° C. In the same way the 2/2 nickel–chromium steel shows evidence of overheating around 1200–1225° C., increasing in severity with increase in temperature, and becoming very marked at 1350° C. In the case of both steels no visible oxide films were evident. Therefore we have ranges of at least 50° C. for the 3% nickel–chromium–molybdenum–vanadium steel and 125° C. for the 2/2 nickel–chromium steel, samples heated in these ranges all exhibiting facet fractures; the only apparent difference for a given steel heated in the ranges quoted is an increase in facet size with an increase in temperature.

(*d*) Following on (*c*) above, the evidence to date, whilst not entirely conclusive, points to a relationship between the austenitic grain-size existing at the overheating temperature, the facet size, and the network revealed by the H_2SO_4/HNO_3 etchant. In other words, facets appear to be derived from the intercrystalline separation of the austenite grains produced by the overheating temperature, the separation in turn being related to some phenomenon occurring at the boundaries.

(*e*) Consideration of the above evidence, in conjunction with the effect of rate of cooling and the effect of forging on overheated 2/2 nickel–chromium steels, suggests very strongly that overheating, of the type under discussion, is a precipitation phenomenon entirely unrelated to outside influences such as atmosphere during heating. In other words the ability to overheat is a function of the steel itself.

A comparison may now be made between the

FIG. 1.—Sample forged from 1300–1280° C.

FIG. 2.—Sample from overheated forging.

FIGS. 1 and 2.—Structures of 2/2 Nickel–Chromium Steel. Etched in sulphuric-acid/nitric-acid reagent. × 100.

observed effects and the idea of a precipitation phenomenon :

Observed.	Precipitation Hypothesis.
(1) Minimum temperature of overheating.	Solution temperature for, say, constituent X.
(2) Range of overheating.	Either increased solution or merely solution with varying austenitic grain-sizes.
(3) Slow rate of cooling.	Sufficiently slow cooling results in precipitation of X around existing austenite boundaries which accounts for increased facet size with temperature. It has been shown with two steels that furnace cooling need not be carried out much below the minimum overheating temperature.
(4) Increased facet size with increase in overheating temperature.	Assuming (3) above, this would be expected owing to increase of austenitic grain-size with temperature.
(5) Quick rate of cooling.	An oil-quenching treatment suppressed facet formation either by (*a*) complete enforced solution, or (*b*) enforced solution down to a certain temperature followed by precipitation at random as distinct from boundary precipitation.
(6) Reduction or elimination of facets by controlled forging.	Forging has no effect on facet formation until precipitation occurs; then X is constantly being dispersed by the process of changing grain boundaries owing to continual deformation and recrystallization. Thus, if the finishing temperature is low enough (assuming adequate work), then no evidence of overheating will be found. If, on the other hand, the finishing temperature is only just below solution temperature then evidence of overheating will be found, but on a smaller grain-size relative to that produced by a simple heating operation.
(7) The presence of several generations of networks after etching with the H_2SO_4/HNO_3 reagent.	It follows from (5) above that, during forging with its continual deformation and recrystallization, a temperature will be reached when precipitation occurs at existing grain boundaries. As there will be several formations of these, there will likewise be corresponding network structures produced. The production of this type of structure will be fairly critical.

(7) *Examination of 3% Nickel–Chromium–Molybdenum Ingot Material.*

Examination of samples selected at random from an annealed 3% nickel–chromium–molybdenum steel ingot, after etching with the H_2SO_4/HNO_3 reagent, showed the presence of coarse cellular boundaries similar to those shown by overheated wrought material. No fractured test-pieces were available in this work, but later a section from an annealed ingot was obtained and submitted to examination. The section permitted examination from the outside to the centre of the ingot, and both fracture tests and micro-examination were carried out at various positions in the ingot after different heat-treatments. Six positions from the outside to the centre of the ingot were utilized, and the following results of fracture tests were obtained, all positions giving similar results for each treatment :

Heat-Treatment.	Appearance of Fracture.
As-annealed.	Very coarse and bright. No definite facets.
O.H. at 850° C., T. 650° C. for 1 hr.	Numerous coarse grey facets.
N. at 1050° C., N. at 950° C., T. 650° C. for 1 hr.	A few coarse facets.
O.Q. at 1350° C., N. at 1050° C., N. at 950° C., T. 650° C. for 1 hr.	No definite facets.

It should be appreciated that fracture tests on cast material are not too satisfactory owing to the tendency for ingotism to predominate. This has also been observed in the 2/2 nickel–chromium steel.

Subsequent micro-examination revealed the presence of heavy networks after etching with the H_2SO_4/HNO_3 reagent, in both the annealed and the hardened and tempered conditions, with and without the prenormalizing and refining treatments. These networks were virtually absent in the specimen originally oil-quenched from 1350° C., although traces of network were still evident. In view of the erratic behaviour of this etching reagent in producing heavy networks, too much stress should not be laid on the results obtained. The conditions leading to maximum response with this reagent are being investigated separately.

(8) *The Effect of Further Heat-Treatment on Material Quickly Cooled from the Overheating Temperature.*

Additional heat-treatment was carried out on both steels to try to produce facets at temperatures of 1100–1150° C., *i.e.*, below the normal overheating temperatures. The basis of this treatment was the assumption that oil-quenching these materials from the overheating range suppresses facet formation (or precipitation), and reheating to some lower temperature *might* produce small

facets (*i.e.*, by precipitation) on the existing grain-size. Oil-quenched material in each case was therefore treated in the manner described and as detailed below.

Samples oil-quenched at 1325° C. were reheated to:

(*a*) 1100° C. for ½, 1, 4, and 8 hr. respectively and then all air-cooled.
(*b*) 1150° C. for ½, 1, 4, and 8 hr. respectively and then all air-cooled.
(*c*) 1150° C. for ½ hr., furnace-cooled to 900° C., held for 1 hr., and air-cooled.

Each treatment was applied to samples of the 3% nickel–chromium–molybdenum–vanadium steel and the 2/2 nickel–chromium steel. None of the treatments resulted in faceted fractures when finally tested after the standard oil-hardening and tempering treatment.

It was found subsequently that treatment (*b*) carried out on samples of the 2/2 nickel–chromium steel with faceted fractures greatly reduced the number and intensity of the facets.

(9) *The Effect of the Method of Steelmaking on the Minimum Overheating Temperature.*

A detailed study of the following four types of acid open-hearth and basic electric-arc steels was carried out:

(*a*) 0·55% Carbon steel.
(*b*) Carbon–chromium steel (En 31).
(*c*) Chromium–molybdenum steel (En 19).
(*d*) Nickel–chromium–molybdenum steel (En 24).

Minimum overheating temperatures were determined in each case using a 1-hr. soaking period at temperature and the standardized furnace-cooling technique previously mentioned. In all cases assessment of the minimum overheating temperature was on the basis of nicked-fracture tests, the presence or absence of facets being recorded. From the same samples a study was made of the grain-growth characteristics of these steels, and the relationship between the grain-size produced by the overheating temperature and the networks observed after etching with the H_2SO_4/HNO_3 reagent. Both features are considered important, when the phenomenon is regarded as one of precipitation, for the following reasons:

If the precipitate is limited in quantity, then the grain-size or grain-boundary area will influence the concentration of the precipitate. Thus, a small grain-size with its consequent large grain-boundary area would have less precipitate per unit area of boundary than correspondingly larger grain-sizes. Therefore the minimum overheating temperature for a given steel might be influenced by the grain-growth characteristics of the material. It was for this reason that the study was made to ascertain whether electric-arc steels had coarser grain-sizes for a given temperature than the corresponding acid open-hearth steels. In other words, accepting the precipitation theory, is the difference in overheating propensities exhibited by open-hearth and electric-arc steels merely a question of grain-size?

Table II. summarizes the data in regard to the minimum overheating temperatures, whilst Table III. gives the grain-size data. No results of the grain-size measurements taken on the samples after etching with the H_2SO_4/HNO_3 reagent have been included in Table III. because the values obtained were not considered reliable owing to the etched networks not being sufficiently continuous. A number of cases, however, showed a reasonable agreement with the grain-size results obtained in the samples in the overheated condition, suggesting that the austenite grain-size existing at the overheating temperature and the network revealed by

TABLE II.—*Analyses and Minimum Overheating Temperatures for Basic Electric-Arc and Acid Open-Hearth Steels.*

Method of Manufacture.	Type of Steel.	Cast No.	Composition, %.											Minimum Overheating Temp., ° C.
			C.	Si.	Mn.	S.	P.	Ni.	Cr.	Mo.	O_2.	H_2.	N_2.	
A.O.H.	0·55% C	23546	0·53	0·23	0·70	0·040	0·030	0·20	0·09	...	0·004	0·003	0·003	Above 1375
B.E.A.	0·55% C	96469	0·56	0·31	0·54	0·008	0·014	0·14	0·05	...	0·003	0·001	0·009	1300–1325
A.O.H.	C–Cr	25606	0·98	0·20	0·39	0·036	0·020	0·16	1·46	...	0·002	0·0002	0·006	Above 1275
A.O.H.	C–Cr	26150	0·98	0·34	0·42	0·022	0·021	0·14	1·46	...	0·002	0·0002	0·004	
B.E.A.	C–Cr	87226	1·0	0·21	0·43	0·015	0·016	0·29	1·35	...	0·003	0·0001	0·011	
B.E.A.	C–Cr	91306	0·99	0·34	0·47	0·010	0·011	0·14	1·34	...	0·003	0·00005	0·012	
A.O.H.	Cr–Mo	25979	0·42	0·26	0·66	0·033	0·029	0·27	1·01	0·28	0·008	0·0002	0·004	Above 1375
B.E.A.	Cr–Mo	91871	0·42	0·30	0·60	0·013	0·013	0·16	1·18	0·26	0·002	0·00005	0·009	1275–1300
A.O.H.	Ni–Cr–Mo	26342	0·40	0·22	0·62	0·03	0·022	1·62	1·16	0·30	0·010	0·0001	0·006	Above 1375
A.O.H.	Ni–Cr–Mo	26410	0·40	0·22	0·61	0·039	0·030	1·62	1·20	0·30	0·009	0·0002	0·005	
B.E.A.	Ni–Cr–Mo	93524	0·41	0·27	0·54	0·008	0·010	1·63	1·14	0·23	0·002	0·0001	0·008	1225–1250
B.E.A.	Ni–Cr–Mo	94123	0·40	0·25	0·62	0·010	0·011	1·68	1·19	0·31	0·003	0·0001	0·006	1275

A.O.H. = Acid open-hearth process. B.E.A. = Basic electric-arc process.

etching have a common basis. That is, the networks represent the original grain boundaries of the austenite grains. Further work in this respect is at present being undertaken.

In general, the results of the determinations indicate that grain-size *per se* is not a major factor in accounting for the differences observed in the facet-forming propensities of open-hearth and electric steels.

(i) 3% Nickel case-hardening steel (En 33).
(ii) 3½% Nickel steel (*S*69).
(iii) 1½% Nickel–chromium–molybdenum steel (En 24).
(iv) Nickel–chromium case-hardening steel (*S*82).

Casts of the first three steels mentioned were made by both the open-hearth and electric processes and

Table III.—*Comparative Grain-Size Data Obtained on Basic Electric-Arc and Acid Open-Hearth Steels.*

	Grain-Size (A.S.T.M.).			
	(*a*) 0·55% *Carbon Steel.*			
	A.O.H. (Cast 23546).	B.E.A. (Cast 96469).		
1300	Mostly 1.	Mostly 1.	...	...
1325	0 with some −1.	(F) 0 with a few larger grains.	...	...
1350	Mixed 1 and 0 with some larger grains.	(F) Mostly 0 with a few larger grains.	...	...
	(*b*) *Carbon–Chromium Steel.*			
	A.O.H. (Cast 25606).	A.O.H. (Cast 26150).	B.E.A. (Cast 87226).	B.E.A. (Cast 91306).
1200	1 with some 0.	2 with some 1 and 0.	1 to 0.	1 with some 0.
1225	1 to 0 (some larger grains).	1 to 2 with some 0.	Mostly 1 and a few larger grains.	Mixed 2, 1, and 0.
1250	1 to 0 (some −1).	0 with a few −1.	−1 with a few −2.	1.
	(*c*) *Chromium–Molybdenum Steel* (*En* 19).			
	A.O.H. (Cast 25979).	B.E.A. (Cast 91871).		
1275	1 (a few 0).	2 to 3 (a few 1).	...	...
1300	0 to 1 (some larger grains).	(F) 1 to 2 (some larger grains).	...	...
1325	0 to −1 (a few −2).	(F) Mostly 1.	...	...
1350	0 to −1.	(F) 0 with some −1.	...	...
	(*d*) *Nickel–Chromium–Molybdenum Steel* (*En* 24).			
	A.O.H. (Cast 26342).	A.O.H. (Cast 26410).	B.E.A. (Cast 93524).	B.E.A. (Cast 94123).
1250	1 to 0.	2 with some 1.	(F) Mostly 1.	1 to 0.
1275	1 to 0.	0 to 1.	(F) 1 with a few 0.	(F) 1.
1300	0 to −1.	Mostly 0.	(F) 1 with some 0.	(F) 1 to 0.
1325	0 to −1 (a few larger grains).	0 to −1.	(F) −1 to −2.	(F) 1 to 0.
1350	0 to −1 (a few −2).	0 to −1.	(F) −1 to −2.	(F) −1 to −2.

(F) denotes a faceted fracture.

The results given in Table II. indicate that the minimum overheating temperature is appreciably affected by the particular method of manufacturing the steel and suggest that, in the main, electric steels are more readily overheated than acid open-hearth steels. In this connection the authors would like to refer to some experiments carried out by Mr. G. L. Talbot of Messrs. Rolls-Royce, Ltd., who has kindly consented to the inclusion of his results in this section of the paper.

Four types of steel were tested:

their chemical compositions are given in Table IV. All the casts of the fourth steel were made in the same electric-arc furnace.

Further details of the experiments and results of the four steels follow:

(i) 3% *Nickel Case-Hardening Steel* (*En* 33).

The heat-treatment given to samples of this steel was:

½-hr. soaking at 1360° C.,
1-hr. soaking at 880° C., A.C.,
O.Q. from 870° C.,
O.Q. from 760° C.

Samples from each cast were fracture-tested for facets with these results:

(a) Acid open-hearth (cast *C*91).	No facets.
(b) Basic open-hearth (cast *V*4563).	No facets.
(c) Basic electric-arc (cast *S*4044).	Some facets.
(d) High-frequency (cast *RE*5841).	Numerous facets.

Repeat tests resulted in similar fractures in the same order of merit.

Both sets of samples were then heated to 1100° C. for 1 hr. and air-cooled. After this second heat-treatment nicked-fracture tests were again carried out from which it was observed that only the high-frequency material showed facets.

New samples of all steels, with the exception of the acid open-hearth cast, were then heated to 1380° C. for 20 min., given the second heat-treatment as before, and fractured.

The following observations were made:

(b) Basic open-hearth (cast *V*4563).	Traces of facets.
(c) Basic electric-arc (cast *S*4044).	Some facets.
(d) High-frequency (cast *RE*5841).	Numerous facets.

Samples of the high-frequency cast (*RE*5841) were heated for 30 min. at temperatures ranging from 1200° to 1400° C. and then again heat-treated as above. Results of nicked-fracture tests were as follows:

Temp., ° C.	
1200	No facets.
1250	No facets.
1300	Some facets.
1350	Marked facets.
1400	Marked facets.

The samples were subsequently heated to 1100° C. for 1 hr., then given the second heat-treatment, as before, and fractured. Facet-free fractures were obtained for those specimens initially treated at and below 1300° C.

In addition to the above, the effect of hot work carried out at the overheating temperature on the appearance of the fracture was explored. Specimens were heated to various temperatures for 30 min., and a reduced-diameter portion was twisted through 90° whilst at the temperature and finally heat-treated. The following results were obtained:

	Temperature, ° C.		
	1200.	1300.	1250.*
(b) Basic open-hearth (Cast *V*4563)	Both untwisted and twisted fractures free of facets.	Both untwisted and twisted fractures free of facets.	...
(c) Basic electric-arc (Cast *S*4044)	Both untwisted and twisted fractures free of facets.	Traces of facets on both fractures.	...
(d) High-frequency (Cast *RE*5841)	Both untwisted and twisted fractures free of facets.	Untwisted fractures free of facets. Twisted fractures showed faint facets.	Both untwisted and twisted fractures free of facets.

* For 15 min., followed by twisting, and then a further 15 min. at 1250° C.

TABLE IV.—*Analyses of Various Steels Manufactured by Different Methods.*

Process.	Cast.	C, %.	Si, %.	Mn, %.	S, %.	P, %.	Ni, %.	Cr, %.	Mo, %.
(i) 3% *Nickel Case-Hardening Steel* (*En* 33).									
(a) Acid open-hearth	*C*91	0·14	0·28	0·53	0·036	0·034	3·19	0·15	...
(b) Basic open-hearth	*V*4563	0·16	0·21	0·47	0·035	0·018	3·24	0·25	...
(c) Basic electric-arc	*S*4044	0·15	0·28	0·50	0·010	0·011	3·00	0·18	...
(d) High-frequency	*RE*5841	0·14	0·22	0·43	0·026	0·010	2·96	0·14	...
(ii) 3½% *Nickel Steel* (S69).									
(a) Acid open-hearth	*A*312	0·39	0·25	0·61	0·040	0·033	3·25	0·20	...
(b) Acid open-hearth	*N*9812	0·39	0·18	0·67	0·036	0·030	3·40	0·21	...
(c) Basic electric-arc	*S*4029	0·40	0·21	0·63	0·012	0·010	3·63	0·28	...
(d) Acid open-hearth	*A*300	0·38	0·25	0·56	0·039	0·037	3·32	0·27	...
(e) ? Duplex	*S*3606	0·35	0·25	0·56	0·012	0·012	3·30	0·20	...
(f) Electric-arc	*B*540	0·38	0·25	0·58	0·012	0·013	3·47	0·15	...
(g) Basic open-hearth	*B*1073	0·38	0·193	0·63	0·039	0·039	3·14	0·22	...
(h) Electric-arc	83763	0·34	0·27	0·61	0·012	0·013	3·55	0·18	...
(iii) 1½% *Ni–Cr–Mo Steel* (*En* 24).									
(a) Acid open-hearth	*B*43	0·38	0·24	0·61	0·05	0·034	1·42	1·0	0·25
(b) Basic open-hearth	*G*4416	0·39	0·26	0·64	0·023	0·023	1·50	0·93	0·32
(c) Acid open-hearth	*W*3709	0·42	0·26	0·63	0·036	0·032	1·50	1·09	0·27
(d) Basic electric-arc	*H*2326	0·38	0·22	0·61	0·012	0·015	1·38	1·05	0·23
(e) High-frequency	*RD*7667	0·36	0·34	0·52	0·026	0·011	1·42	0·96	0·27
(f) Acid open-hearth	*B*43	0·38	0·24	0·61	0·05	0·034	1·42	1·0	0·25
(g) Basic open-hearth	*G*4416	0·39	0·265	0·64	0·023	0·023	1·50	0·93	0·32
(h) Basic electric-arc	85647	0·41	0·31	0·51	0·014	0·024	1·71	1·05	0·35

(ii) $3\frac{1}{2}\%$ *Nickel Steel* (S69).

The samples were given the following heat-treatment:

30-min. soaking at 1360° C. or
20-min. soaking at 1380° C., then
1-hr. soaking at 880° C., A.C.,
T. 600° C., A.C.

Results of fracture tests were as follows:

	Overheating Temperature. 1360° C.	1380° C.
(*a*) Acid open-hearth (cast *A*312).	No facets.	...
(*b*) Acid open-hearth (cast *N*9812).	Some facets.	Numerous facets.
(*c*) Basic electric-arc (cast *S*4029).	Some facets.	Numerous facets.

Additional samples of this steel were heated to 1350° C. for 1 hr., followed by the second heat-treatment as before. The appearances of the fractures and of the microstructures after etching with the H_2SO_4/HNO_3 reagent were as given below:

	Fracture.	After Etching.
(*d*) Acid open-hearth (cast *A*300).	No facets.	No network.
(*e*) ? Duplex (cast *S*3606).	Facets.	Large network.
(*f*) Electric-arc (cast *B*540).	Facets, but finer than above.	Network, but not continuous.
(*g*) Basic open-hearth (cast *B*1073).	No facets.	No network.
(*h*) Basic electric-arc (cast 83763).	Facets (as in cast *B*540).	Network, but not continuous.

(iii) $1\frac{1}{2}\%$ *Nickel–Chromium–Molybdenum Steel* (*En* 24).

Samples were heated to one of the following temperatures: 1360° C. (30 min.), 1380° C. (20 min.), or approximately 1480° C. (30 min.). Each sample then received the following heat-treatment:

1 hr. at 880° C., A.C.,
O.Q. from 830° C.,
T. 680° C., A.C.

Corresponding appearances of the nicked fractures (where carried out) were:

	1360° C.	1380° C.
(*c*) Acid open-hearth (cast *W*3709).	No facets.	Some facets.
(*d*) Basic electric-arc (cast *H*2326).	No facets.	Numerous facets.
(*e*) High-frequency (cast *RD*7667).	Traces of facets.	Some facets.
(*f*) Acid open-hearth (cast *B*43).	No facets.	...
(*g*) Basic open-hearth (cast *G*4416).	...	...

Samples of steels (*c*), (*d*), (*e*), and (*g*) which had been initially heated to approximately 1480° C., were heated at 1100° C. for 1 hr. before final heat-treatment. The fractures of these samples showed numerous facets.

Further work on samples of the electric-arc steel (*d*) was carried out as follows:

	Temp., ° C. (30 min.).	Fracture.
	1250	Traces of facets.
	1350	Numerous facets.
	1400	Numerous facets.
All preheated for 1 hr. at 700° C.	1250	Traces of facets.
	1350	Numerous facets.
	1400	Numerous facets.
	1350, 1400 followed by 1 hr. at 1100° C. before heat-treating.	Some facets in each case, but an improvement on those above.

Other samples of this type of steel were heated to 1380° C. for 20 min., and finally treated as follows:

1 hr. at 880° C., A.C.,
O.Q. from 830° C.,
T. 620° C.

Results of fracture tests are shown below:

(*f*) Acid open-hearth (cast *B*43)	No facets.
(*g*) Basic open-hearth (cast *G*4416).	Traces of facets.
(*h*) Basic electric-arc (cast 85647).	Numerous facets.

A repeat experiment was made using samples air-cooled after 1 hr. at 1100° C. instead of at 880° C. before the final heat-treatment, with the following results:

(*f*) Acid open-hearth (cast *B*43).	No facets.
(*g*) Basic open-hearth (cast *G*4416).	No facets.
(*h*) Basic electric-arc (cast 85647).	Numerous facets.

(iv) *Nickel–Chromium Case-Hardening Steel* (S82).

All material used in these tests was made in the same electric-arc furnace, the individual casts being successive and numbering 28. A temperature of 1370° C. for 30 min. (furnace-cooled) was employed for overheating, and there were two subsequent treatments before fracturing:

(*a*) 1 hr. at 900° C., A.C.; 840° C., O.Q.; 760° C., O.Q.
(*b*) 1 hr. at 1100° C., A.C.; 840° C., O.Q.; 760° C., O.Q.

The response to the temperature was variable, some samples being virtually free of facets whilst others showed very numerous facets. All casts were improved by the intermediate treatment of heating to 1000° C., but it was not always effective in obliterating the overheating effects. Two casts were refined at 1100° C. which did not appreciably affect the fracture, whereas refining at 1100° C. almost entirely eliminated the facets.

(10) *The Effect of Aluminium Additions on the Minimum Overheating Temperature.*

After the above series had been completed the general subject was discussed with Mr. Preece who indicated that, on the basis of a limited number of results, there appeared to be a correlation between minimum overheating temperature and total oxygen content. This, of course, was in line with the behaviour of open-hearth and electric-arc steels and indicated that the lower the oxygen content the lower was the minimum overheating temperature; therefore if oxygen *per se* was a factor then it must be an indirect one.

Tests were carried out on six classes of steel:

(i) Carbon–chromium steel (En 31).
(ii) 3% Nickel–chromium–molybdenum and nickel–chromium–molybdenum–vanadium steels.
(iii) 2/2 Nickel–chromium steel.
(iv) Chromium–aluminium (nitralloy) steel.
(v) Chromium–manganese steel (En 18).
(vi) Nickel–chromium–molybdenum steel (En 24).

The chemical composition of each steel and its method of manufacture are given in Table V.

TABLE V.—*Analyses of Casts before Aluminium Additions.*

Type of Steel.	C, %.	Si, %.	Mn, %.	S, %.	P, %.	Ni, %.	Cr, %.	Mo, %.	V, %.	Al, %.	Dia. of Material used, in.
(i) *C–Cr Steel (En* 31).											
Electric-arc	1·01	0·25	0·39	0·007	0·014	0·18	1·37	...	...	...	$1\frac{1}{8}$
(ii) 3% *Ni–Cr–Mo–V and* 3% *Ni–Cr–Mo Steels.*											
(*a*) Basic electric-arc (cast 78226)	0·32	0·14	0·54	0·016	0·017	2·77	0·69	0·53	0·16	...	1 (sq.)
(*b*) Basic electric-arc (cast 91672)	0·30	0·29	0·64	0·007	0·012	3·17	0·83	0·66	...	...	1 (sq.)
(iii) 2/2 *Ni–Cr Steel.*											
Electric-arc	0·57	0·32	0·10	0·008	0·008	2·38	2·29	...	...	...	$\frac{3}{4}$
(iv) *Cr–Al (Nitralloy) Steels.*											
(*a*) Acid open-hearth (cast 24558)	0·29	0·18	0·59	0·022	0·024	0·13	1·58	0·19	...	1·11	$5\frac{1}{4}$
(*b*) Basic electric-arc (cast 98411)	0·26	0·24	0·55	0·015	0·015	0·30	1·59	0·26	...	1·0	1
(*c*) Basic electric-arc (cast 93498)	0·43	0·34	0·52	0·012	0·011	0·20	1·60	0·24	...	0·97	$\frac{7}{8}$
(*d*) American (cast 42*M*473)	0·42	0·30	0·59	0·040	0·020	...	1·58	0·20	...	1·15	$\frac{3}{4}$
(v) *Cr–Mn Steel (En* 18).											
(*a*) Acid open-hearth (cast 25424)	0·47	0·25	0·85	0·028	0·026	0·18	0·90	...	...	...	$\frac{3}{4}$
(*b*) Acid open-hearth (cast 24273)	0·43	0·14	0·73	0·034	0·026	0·30	0·89	...	...	...	$\frac{1}{2}$
(vi) *Ni–Cr–Mo Steel (En* 24).											
(*a*) Acid open-hearth (cast 27205)	0·37	0·25	0·66	0·035	0·025	1·74	1·23	0·35	...	...	$2\frac{1}{2}$

(i) *Carbon–Chromium Steel (En* 31).

About the same time work was being carried out on the effect of aluminium additions in a cast of carbon–chromium electric-arc steel (En 31), with a view to determining the grain-growth characteristics of material in various states of deoxidation; this work was therefore linked up with the previous work on open-hearth and electric-arc casts. Such tests on open-hearth steel would have been preferable, since electric-arc steel is generally considered to be well deoxidized as compared with open-hearth material, but the cast mentioned above was available and so was used for this work.

An addition of 1 lb. of aluminium was made to the bath (approximately 10 tons) before tapping, and then individual ingots were treated with aluminium. The additions of aluminium to each individual ingot and the gas analyses of the individual rolled bars were as follows:

Ingot.	Aluminium, %.	O_2, %.	H_2, %.	N_2, %.
A	0·008	0·0035	0·00005	0·007
B	0·004	0·0025	0·00005	0·009
C	0·002	0·0030	0·00005	0·008
D	Nil	0·0035	0·00005	0·009

Rolled bars of $1\frac{1}{8}$-in. dia. representing each ingot were heated at various temperatures for 1-hr. periods, slowly cooled, refined, water-hardened, tempered, and then nick-fractured. In each case the minimum overheating temperature was found to be within the range 1200–1225° C.

Whilst the increase of aluminium did not appear to affect the minimum overheating temperature, it did affect the appearance of the fracture by correspondingly increasing the facet size for a given overheating temperature. Furthermore, increase in aluminium content rendered the facets much more discernible, the effect being to alter the texture of the facet and improve its contrast against the normal grey background. It should be stated here that the contrast in fractures containing facets is generally poor for carbon–chromium steel under the conditions of test used, and it is possibly this feature which gave negative results in the case of the samples examined in section (9).

Grain-size data were recorded in the usual manner, and the results, given in Table VI., show that, in general, increased aluminium additions resulted in increased grain-size for a given temperature, but had no influence on the minimum overheating temperature. Where facet fractures were obtained, their size corresponded with the grain-size obtained by micro-examination.

Table VI.—*Grain-Size Data Obtained on Aluminium-Treated Basic Electric-Arc Carbon–Chromium Steels.*

Heating Temp., ° C.	Al, %.	Grain-Size (A.S.T.M.), As-Heated.
1200	Nil	1 to 2
	0·002	0 to 1
	0·004	1, with some 2 and 0
	0·008	0, with some 1, a few −1
1225	Nil (F)	1 to 2
	0·002 (F)	0 to −1
	0·004 (F)	−1, (few smaller and larger grains)
	0·008 (F)	−2
1250	Nil (F)	Mostly 0
	0·002 (F)	0, with some −1 and −2
	0·004 (F)	−1 to −2
	0·008 (F)	−2 to −3
1275	Nil (F)	1 to −1
	0·002 (F)	0 to −1
	0·004 (F)	0 to −1
	0·008 (F)	−1 to −2, with some larger grains.

(F) denotes a faceted fracture.

(ii) 3% *Nickel–Chromium–Molybdenum and Nickel–Chromium–Molybdenum–Vanadium Steels.*

At the same time further work was put in hand in connection with 3% nickel–chromium–molybdenum (with and without vanadium) steels, different casts being used from hitherto (section (3)). The minimum overheating temperature was determined as before for each steel.

The following results were obtained:

O_2, %.	H_2, %.	N_2, %.	Min. Overheating Temp., ° C.
(*a*) Basic Electric-Arc, Ni–Cr–Mo–V Steel (Cast 78226).			
0·003	0·0001	0·011	1300–1325
(*b*) Basic Electric-Arc, Ni–Cr–Mo Steel (Cast 91672).			
0·004	0·0001	0·013	1250–1275

Comparison of the above results with the earlier work on similar steels shows that whilst the present vanadium-bearing steel had approximately the same minimum temperature of overheating as hitherto, the results of the vanadium-free steel showed that the minimum temperature was approximately 100° C. lower than the temperature established in the previous series. The above result was confirmed by repeat tests.

Examination of the charge sheets showed that whereas the earlier casts were treated with 7 lb. of aluminium for an approximately 16-ton charge (4 lb. added to bath and 3 lb. added to ladle) the present nickel–chromium–molybdenum steel (cast 91672) having the low overheating temperature was an experimental cast and had been treated with the following considerably larger quantities of aluminium in addition to calcium silicide:

15 lb. of aluminium added to bath before finishings.
12 lb. of aluminium added to bath before tapping.
67 lb. of calcium silicide added to ladle.

This led to the search for available casts which offered a basis of comparison on the effect of aluminium and/or calcium silicide additions.

(iii) 2/2 *Nickel–Chromium Steel.*

Two ingots from an electric-arc cast were available, one of which had been treated with aluminium and the other of which had not. Ingot *EX*656 had no aluminium addition, and ingot *EX*655 had an addition of 0·01%. Samples of $\frac{3}{4}$-in. dia. rolled bar were tested in each case, with the following results:

	O_2, %.	H_2, %.	N_2, %.	Min. Overheating Temp., ° C.
*EX*656	0·004	0·00005	0·008	1225–1250
*EX*655	0·002	0·00005	0·007	1150–1175

Grain-size data corresponding to various temperatures are as follows:

Overheating Temp., ° C.	*EX* 656.	*EX* 655.
1150	2 to 1	2 to 1
1175	1	2 to 1
1200	1 to 2	0 to 1
1225	0 to 1	1 with some 0
1250	0 to 1	0 with some −1

(iv) *Chromium–Aluminium* (*Nitralloy*) *Steels.*

A number of casts were available, amongst which was an acid open-hearth cast for comparison with an electric cast. The inclusion of the open-hearth cast was considered interesting, since previous work had indicated that aluminium additions in some electric-arc casts appeared to influence the overheating temperature. This naturally suggested that the difference between open-hearth and electric-arc steels was one of deoxidation and, whilst aluminium influenced electric-arc steels to some extent, such additions might be expected to have a much greater influence on open-hearth material because of the much higher overheating temperatures observed in steels made in this way. In other words, it could be argued that electric-arc steel is generally in a well deoxidized condition without aluminium additions, and treatment with the latter would not necessarily influence the overheating temperature. Open-hearth steel, on the other hand, is much less deoxidized and thus additions of aluminium (in this case 1%) might reduce the overheating temperature approximately to that of the corresponding electric-arc steel. It was realized, of course, that the effect of an addition as much as 1% may introduce some other factor to influence the overheating temperature.

Of the steels tested (given in Table V.), only casts 24558 and 98411 are directly comparable because of the higher carbon contents of the other two steels. The size of material used for each cast was as follows:

Cast.	Bar Dia., in.
24558	$5\frac{1}{4}$
98411	1
93498	$\frac{7}{8}$
42*M*473	$\frac{3}{4}$

Examination of fractures failed to reveal facets in any of the casts up to 1360° C. The tests at 1375° C. showed evidence of incipient melting and were therefore not suitable for examination for facets.

(v) *Chromium–Manganese Steel* (*En* 18).

Two acid open-hearth casts were available, one having a greater aluminium addition than the other. No electric-arc cast was available, however, so that relative behaviour could not be judged in regard to open-hearth against electric-arc steel. The material used for cast 25424 was $\frac{3}{4}$-in. dia. bar; an aluminium addition of 20 lb. was added to the bath (55-ton charge). Cast 24273 was in the form of $\frac{1}{2}$-in. dia. bar, and 21 lb. of aluminium had been added to the 35-ton charge in the bath. The following data were recorded:

	O_2, %.	H_2, %.	N_2, %.	Min. Overheating Temp., ° C.
(*a*) Cast 25424	0·006	0·00005	0·006	Above 1375
(*b*) Cast 24273	0·002	0·0002	0·002	1350–1375

Whilst the difference in minimum overheating temperature is not quite as much as might be expected, the trend is in the direction indicated by some of the previous experiments. It should be realized, of course, that the samples used were from different casts and that the position of the material in the cast was unknown. In addition, there was no information available as to the behaviour of electric-arc casts of similar composition.

(vi) *Nickel–Chromium–Molybdenum Steel* (*En* 24).

In view of the foregoing results it was decided to determine by direct means whether aluminium additions would influence the overheating temperature of acid open-hearth steel; consequently different amounts of aluminium were added as a mould addition to a nickel–chromium–molybdenum steel (En 24). It was hoped to ascertain whether the overheating temperature could be lowered to the level of that of an electric-arc cast, *i.e.*, from some temperature in excess of 1375° C. to, say, 1250–1275° C. or even lower. The aluminium additions were as follows:

Ingot.	Aluminium Addition, oz./ton.
C	Nil
D	1
E	2
F	4
G	8
H	16

In view of its well-known deoxidation properties 8 lb. of Silcaz per ton were added to ingot *I*.

The overheating experiments were carried out on quartered $2\frac{1}{2}$-in. dia. bar and the results and gas analyses are given in Table VII.

Consideration of the results indicates a rather erratic response to the aluminium treatment, but this may be influenced by the effect of cooling rate from the overheating temperature (*see* Discussion below). The results, however, do indicate that the minimum overheating temperature of an open-hearth cast can be influenced by aluminium additions.

(11) *Vacuum-Melting Experiments.*

Parallel with the foregoing experiments a vacuum-melting technique was developed utilizing the nickel–chromium–molybdenum steel (En 24)

(acid open-hearth cast 26410) which had been found to have an overheating temperature in excess of 1375° C. as distinct from the temperature of 1250–1275° C. obtained on the corresponding electric-arc casts. The line of thought in regard to this particular experiment was to check whether the comparatively low overheating temperatures observed on electric-arc casts were a phenomenon peculiar to the particular steel-making process and independent of deoxidation (or oxygen content). Thus, a sample of a 1¾-in. sq. billet in the as-rolled condition was machined to produce a sample which would fit an alumina crucible to produce a small tapered ingot of 1½ in. dia. at the top, 1 $\frac{1}{32}$ in. dia. at the bottom, and 4 in. in length.

The figures in brackets are the grain-sizes obtained on the material before vacuum-melting for comparison with the vacuum-melted material.

As changes in composition were probable, an analysis was made of the vacuum-melted material, and is presented below together with the cast analysis:

	C, %.	Si, %.	Mn, %.	S, %.	P, %.	Ni, %.
Vacuum melt	0·35	0·25*	0·005	0·010	0·034	1·5*
Cast . .	0·40	0·22	0·61	0·039	0·030	1·6

	Cr, %.	Mo, %.	O_2, %.	H_2, %.	N_2, %.
Vacuum melt	1·2*	0·3*	0·0009	0·0005	0·0002
Cast . .	1·2	0·30	0·009	0·002	0·005

* Obtained by spectrographic analysis.

In view of the above changes in composition and the fact that the minimum overheating tempera-

Table VII.—*Response to Overheating of Aluminium-Treated Nickel–Chromium–Molybdenum Steels.*

All samples were refined by normalizing from 950° C., O.H. 850° C., T. 650° C. before fracturing.
No facets appeared after heating for 1 hr. at 1300° C.

Ingot.	Aluminium Addition, per ton.	Additional Analysis, %.				Appearance of Fracture after Heating for 1 hr. at:		
		S.	O_2.	H_2.	N_2.	1325° C.	1350° C.	1375° C.*
C . .	Nil	0·037	0·003	0·00005	0·004	No facets.	No facets.	No facets.
D . .	1 oz.	0·036	0·005	0·0002	0·003	Suspicion of facets.	Small but definite facets.	Facets.
E . .	2 oz.	0·036	0·005	0·0001	0·004	Suspicion of facets.	Suspicion of facets.	Facets.
F . .	4 oz.	0·034	0·004	0·0001	0·004	Suspicion of facets.	Suspicion of facets.	Facets.
G . .	8 oz.	0·032	0·003	0·0001	0·003	No facets.	No facets.	Facets.
H . .	16 oz.	0·033	0·002	0·0001	0·006	No facets.	No facets.	Facets.
I . .	8 lb. Silcaz.	0·030	0·005	0·0002	0·007	No facets.	No facets.	Facets.

* Maximum effect appears to be with ingots *D* and *E*.

The sample was heated at 1650–1700° C. for 1 hr. and furnace-cooled. This was followed by a further period of 1 hr. at 1550–1600° C. and furnace-cooling. In each case the melting was carried out under a vacuum of 0·001 mm. of mercury. What atmosphere was present was largely made up of carbon monoxide and hydrogen.

The ingot was well forged to a ½-in. dia. bar, and used for determinations of overheating temperatures. Fracture testing gave the following results:

Heating Temp., ° C.	Appearance of Fracture.
1275	Numerous facets.
1300	Numerous and large facets.
1325	Numerous and very large facets.

The facets were far larger than those found in the corresponding electric-arc steels.

Grain-sizes were recorded as follows:

Overheating Temp., ° C.	Grain-Size (A.S.T.M.), As-Overheated.
1275	−2 (0 to 1)
1300	−3 (mostly 0)
1325	−4 (0 to −1)

ture had not been attained, it is intended to carry out repeat melts.

Discussion.

No definite conclusions can be drawn at this stage of the work as to the actual cause of the faceted fractures obtained when steels are heated to high temperatures. Nevertheless there appear to be several interesting trends developing which are based on the following observations:

(*a*) There appears to be a minimum temperature above which overheating (synonymous with faceted fractures) occurs over a fairly wide range of temperature.

(*b*) The minimum overheating temperature varies with different steels and with different casts of apparently the same steel.

(*c*) Further to (*b*), the method of steelmaking has an important influence on the minimum overheating temperature, basic electric-arc steels having considerably lower minimum overheating temperatures than corresponding open-hearth

steels. Furthermore, aluminium additions (and possibly calcium silicide) appear in some cases to lower the minimum overheating temperature.

(*d*) The vacuum-melting experiments, though limited, indicate that this method of melting can bring about a substantial lowering of the minimum overheating temperature. Therefore low minimum overheating temperatures are not necessarily peculiar to the basic electric-arc process.

(*e*) The limited work carried out on the nickel–chromium–molybdenum ingot samples (section (7)) suggests that the overheating tendencies of a steel are an inherent factor in the material itself and are not the result of outside influences such as the atmosphere during overheating (*see* section (4)).

(*f*) Whilst the evidence is limited at the moment, it is fairly certain that facet size, austenitic grain-size at the overheating temperature, and the network revealed by the special H_2SO_4/HNO_3 etch are inter-related.

(*g*) The rate of cooling from the overheating temperature is an important factor in the development of faceted fractures. Thus a quick rate of cooling tends to suppress facet formation whilst the furnace-cooling technique adopted in the present work develops faceted fractures if the reheating temperature is sufficiently high. On the other hand, more recent work has shown—as Mr. Preece has also—that the rate of cooling for certain steels if too slow may also result in facet-free fractures. Thus the indications are at the moment that the rate of cooling is a critical factor in forming faceted fractures, provided, of course, that the material is heated above the established minimum overheating temperature; and it is probable that the rate of cooling which produces the most pronounced facets will differ for different steels.

(*h*) Forging from a temperature above the minimum overheating temperature established by straight heating experiments has a considerable influence on the appearance of the final fracture as witnessed by the experiments on the 2/2 nickel–chromium steel (section (5)). Thus, by this means, the minimum overheating temperature is apparently raised some 75–100° C. and in the case where facets were observed in the fracture, forging also appears to have reduced the facet size considerably. A further important point is that heating to a temperature above the minimum overheating temperature does not necessarily affect the forging behaviour of the steel. Moreover, the results also suggest that as long as the amount of reduction is adequate and the finishing temperature low enough, faceted fractures which would be expected from the temperatures employed are eliminated.

On the basis of the observations made, a hypothesis is put forward that faceted fractures are due to a precipitation of an unknown constituent around the austenite grain boundaries existing at the overheating temperature. Further, this constituent is already present in steels as cast, and with a sufficiently high temperature and a correct rate of cooling, a critical concentration of the constituent is precipitated at the austenite boundaries existing at that temperature. This concentration results in a series of interruptions of the crack induced in the usual nicked-fracture test, giving rise to the well-known appearance of the faceted fracture.

How the effect of the steelmaking process influences the minimum overheating temperature is still a matter to be determined, but several interesting factors have been obtained in the work which is following on the present paper. In this connection Mr. Preece originally put forward the idea that there appeared to be a correlation between oxygen content and minimum overheating temperature, though the influence was probably an indirect one since the lower the oxygen content the lower appeared to be the minimum overheating temperature. He has shown more recently that the correlation is not a good one, but it may be affected by other factors such as sulphur and inclusion contents. In general, the present results indicate that lower oxygen contents (other factors being constant) are synonymous with low overheating temperatures, although several anomalies exist. The oxygen factor, however, may readily account for the influence of aluminium additions on the minimum overheating temperature, although here again the results obtained are not entirely in agreement with the expectations. This is particularly so in regard to the experiments dealing with the influence of aluminium additions to an acid open-hearth cast of nickel–chromium–molybdenum steel (section (10)). The response to overheating does not increase continuously with the aluminium addition. Further work on the effect of cooling rate may throw some light on the matter.

When oxygen contents are low (as in the basic electric-arc process compared with the acid open-hearth) other elements such as sulphur and phosphorus are lowered so that at least three variables exist in this connection. Mr. Whiteley's observation that sulphur (as sulphides) appears to be dissolved at overheating temperatures is interesting, since sulphur is one of the elements which is low in the basic electric-arc process and which was reduced considerably in the vacuum-melting experiment (section (11)). Present experiments show that sulphur tends to have an influence on the propensity to facet formation. Thus, a nickel–chromium–molybdenum steel of basic electric-arc origin was modified such that one ingot was treated with iron sulphide to produce a sulphur content comparable with a Siemens

cast. The following were the analyses before (*H*) and after (*I*) the modification:

Ingot.	C, %.	Si, %.	Mn, %.	S, %.	P, %.	Ni, %.
H .	0·31	0·24	0·64	0·012	0·015	3·70
I .	0·31	0·24	0·64	0·046	0·015	3·70

Ingot.	Cr, %.	Mo, %.	O_2, %.	H_2, %.	N_2, %.
H .	0·89	0·36	0·002	0·0001	0·007
I .	0·89	0·36	0·002	0·0001	0·009

The results to date show that whilst there does not appear to be a wide difference in the minimum overheating temperatures, there certainly is a remarkable difference in the ease of producing facets. Thus, the low-sulphur cast gives numerous and well developed facets, the formation of which is not affected by the cooling rate from the overheating temperature over wide limits. The high-sulphur cast, on the other hand, produces only a few poorly developed facets over a fairly wide range of overheating temperatures. In addition, the high-sulphur cast seems more susceptible to variations in the cooling rate than the low-sulphur cast. Sulphur, therefore, does appear to affect the facet-forming tendencies of a material. These experiments also suggest that the effect of the rate of cooling on all types of steel—particularly those of open-hearth origin—requires exploration to determine their true susceptibility to overheating.

The minimum overheating temperature may also be influenced by the state of combination of the sulphur, and hence by the manganese content. It is evident that much further work is required and the points raised are being explored. It is hoped to deal more fully with these in a later paper.

ACKNOWLEDGMENTS.

In conclusion the authors would express their thanks to Dr. C. Sykes, F.R.S., not only for his permission to publish the paper, but also for his guidance in this work and for the facilities provided; also to members of the staff of the Brown-Firth Research Laboratories, particularly to Mr. C. C. Gegg and Mr. R. McGavin, for assistance during the investigations.

[This paper was discussed jointly with the preceding four by H. J. Merchant on "Some Aspects of the Overheating of Steel Drop-Forgings," by A. Preece, A. Hartley, S. E. Mayer, and J. Nutting on "The Overheating and Burning of Steel," by W. E. Goodrich on "Overheating and Burning of Nickel–Chromium–Molybdenum Steel," by F. C. Thompson and L. R. Stanton on "The Effect of Oxygen on the Isothermal Transformations of Steel, and a Suggested Test for Burning."]

Discussion on

OVERHEATING AND BURNING OF STEEL.

The following five papers were discussed jointly: "Some Aspects of the Overheating of Steel Drop-Forgings," by H. J. Merchant; "The Overheating and Burning of Steel," by A. Preece, A. Hartley, S. E. Mayer, and J. Nutting; "Overheating and Burning of Nickel–Chromium–Molybdenum Steel," by W. E. Goodrich; "The Effect of Oxygen on the Isothermal Transformations of Steel, and a Suggested Test for Burning," by F. C. Thompson and L. R. Stanton; and "Some Experiments on Overheating," by J. Woolman and H. W. Kirkby.

(Figs. D to I = Plates XXA and XX.)

Dr. J. W. JENKIN (Member of Council) (Tube Investments, Ltd., Birmingham) (in the course of presenting the five papers) said: It is likely that Mr. Merchant's evidence for the effect of time and of atmosphere is not conclusive, for it is clear from the other papers that his views do not hold good. While it may be true, as he implies, that the higher the alloy content, the greater the susceptibility to overheating, the other workers have not found a correlation with composition. The other workers agree with him in saying that electric-furnace material is more susceptible to overheating than basic open-hearth. His suggestion that fracture standards should be prepared in each plant, with the checking of each cast of steel for susceptibility to overheating, is not one that will commend itself widely, and it is to be hoped that the work described in some of the other papers will eventually make such elaborate examination unnecessary. Mr. Preece and his co-workers have made an important contribution to our knowledge of the subject; perhaps the most valuable part is the section dealing with the importance of the rate of cooling after overheating. Evidently there are many cases in which the damage that has been done can be eliminated by slowly cooling from the high temperature concerned down to somewhere just below the incipient overheating temperature, below which cooling rate does not matter at all. It seems that Mr. Goodrich would not agree with that conclusion, for he says that it is the rate of cooling through the transformation range that matters. A related difference is that while Mr.

Goodrich's fracture *D* (" granular with bright crystalline facets ") was produced by oil-quenching from the overheating temperature, and fracture *E* (" granular with dull grey intercrystalline facets ") by slowly cooling in asbestos, Mr. Preece says that furnace-cooling (and water-quenching) both tend to suppress overheating characteristics. This may be cleared up when the investigators come to compare cooling rates quantitatively. Mr. Goodrich refers in his very opening paragraph to the effect of slow cooling in eliminating the abnormal fractures and, in his fourth conclusion, to the fact that a granular fracture is not produced unless the steel is rapidly cooled through the upper critical range; nevertheless he sometimes obtains the granular fracture on " slow cooling in asbestos." He says in his conclusions that evidence of overheating may occur in material that is not, in fact, overheated. I have been looking into the paper for some evidence for this statement, but so far without success. It is clear that both Mr. Goodrich and Mr. Preece lean towards the same sort of view of the mechanism, *i.e.*, some association with a change in austenite grain boundaries whereby the relative strengths of the crystals and their boundaries are affected. Messrs. Woolman and Kirkby, judging from their section 6(*d*) on p. 268 P, would be reluctant to accept Mr. Preece's refutation of any correlation between incipient overheating temperature and austenitic grain-size. The bearing on the other papers of the work of Professor Thompson and Professor Stanton, apart from showing that isothermal behaviour does not provide a test for burning, is that at any rate there is a difference between the burnt and unburnt steel as regards the constituents present. They do not however say whether they use the term " burnt " in the same sense as Messrs. Preece and Goodrich, *i.e.*, involving incipient fusion.

Mr. A. Preece (Leeds University): Dr. Jenkin has given us such an admirable summary of the papers that it only remains for me to indicate some of the more important features of our work and to refer to certain differences in the conclusions arrived at by the various authors.

When we commenced this investigation about two years ago, it was well known that steels made to the same specification and sometimes consecutive casts from the same furnace, showed wide variations in their overheating properties. It was also known that open-hearth steels were less prone to overheating troubles than those made in the electric furnace. It seemed desirable, therefore, to determine in the first instance the overheating tendencies of a large number of steels, and to select for more detailed examination those which showed rather unusual overheating properties.

To summarize our results very briefly, it may be said that we have established overheating as an inherent property of a steel and that, although overheating and burning give rise to similar fractures, they are quite different phenomena.

It must be emphasized that the degree of overheating depends not only on the temperature to which the steel is heated, but also on the rate of cooling to the incipient overheating temperature. It is during the cooling through this short temperature range that the diffusion processes, which are responsible for the overheated condition, actually take place, and it is significant that very slow cooling or, to a lesser extent, quenching, prevents or largely minimizes this effect.

From fracture and etch tests, it is evident that this diffusion process so alters the composition of the metal in the region of the austenite crystal boundary that it differs from the rest of the crystal in its response to toughening by heat-treatment and the faceted or granular fracture is merely a consequence of this.

Soaking time is of importance only above the incipient overheating temperature, and then only in so far as it produces grain growth. Under these conditions, however, temperature has a much more important effect on the crystal size than has prolonged heating.

We have not carried out many tests above 1375° C., but so far we have found no evidence of oxide films or tarnish colours on steel that has not been burnt. In this respect we differ from Merchant, who states that he has found these oxide films and tarnish colours on overheated steel. We also think that " crozzling " is of very doubtful value for assessing overheating, as it probably indicates nothing more than the grain-size.

Results obtained with a large number of steels have indicated to us certain dangers in attempting to assess from standard fractures the embrittlement of a steel as suggested by Merchant, since the relationship between these two factors varies from cast to cast. A much better method would be to determine the overheating temperature of each cast of steel. This could easily be made a routine test, and casts having pronounced overheating tendencies could then be noted and due care taken in heating for forging.

Goodrich concludes that rapid cooling through the upper critical range is necessary to produce the granular type of fracture. I presume this is intended to mean that this treatment is necessary merely to produce a suitably toughened steel after appropriate tempering. There does not appear to be anything fundamentally important in the fact that the steel passes rapidly through the upper critical point.

Goodrich also states that signs of overheating

may be masked by slow cooling; we should be grateful if he would explain what this effect is.

There seems to be a fair amount of agreement between our results and those of Woolman and Kirkby, but we find some difficulty in accepting their precipitation theory. We have failed to find any evidence of a precipitate in highly overheated steels and Figs. 34 and 35 of our paper show that the grain-boundary effect has substantial dimensions, and is clearly not a precipitate.

It is unfortunate that "furnace cooling" in Woolman and Kirkby's paper and in ours does not mean the same thing. In our paper, it refers to a cooling rate of 3° C./min., which is slow enough to suppress overheating, while in the other paper it signifies a rate of 20° C./min., which we have found does not suppress overheating. In comparing results given in both papers, this difference in the term "furnace cooling" must be borne in mind.

The results given in Table I. in Woolman and Kirkby's paper are difficult to understand, because we should have expected facets in all these samples.

Experiments by these authors, in which additions of aluminium have been made to a series of ingots, have provided most valuable information, and it is to be hoped that they will continue these experiments.

Thompson and Stanton have shown that isothermal transformation work has not been very helpful in studying burnt steels; this may not be the case in dealing with overheating phenomena and may be well worth further study.

Mr. W. E. Goodrich (Messrs. Wm. Beardmore & Co., Ltd., Glasgow): I should like to pay tribute to Dr. Jenkin for his very careful summary and comparison of the recorded results of the numerous investigations. He omitted, however, to propose a vote of thanks to me for giving him such little printed matter to read! However, some of that little seems, at first sight, to be rather in conflict with the statements made by other investigators, particularly by Mr. Preece and his colleagues.

Dr. Jenkin referred to my statement that evidence of overheating may occur in material that is not in fact overheated. It is possible to get a granular type of fracture on test material, say, from a forging, and that material can still show typical mechanical properties. Also, the faceted type of fracture can be eliminated by re-oil-hardening and tempering that forging. Therefore, the material could not have been really overheated.

Mr. Preece made reference to the statement that it was clear that signs of overheating in steels might be masked by slow rates of cooling. In Fig. 1 of my paper, fracture *B*—a silky transcrystalline fracture, with not very marked grain-boundary outlines—was produced by overheating temperatures of 1350° or 1400° C. That fracture does not show the faceted type of intercrystalline breaks. Fracture *C* was produced by using overheating temperatures within the range 1250–1400° C., followed by slow cooling to 850° C. This procedure produced a transcrystalline path of fracture, the crystals often showing twinning and having very marked boundary outlines, but not the faceted fracture that we associate with overheating. If material that has been subjected to a temperature of, say, 1350° C. or 1400° C. and which has the type of fracture depicted by *B* or *C*, is subsequently oil-hardened at 850° C. and tempered, it then produces a fracture of the type shown by *E*, which is one we associate with overheating. Therefore with fractures of types *B* and *C* the steel is overheated, but the fracture does not show that overheated effect until the steel is hardened and tempered. This also answers the question raised by Mr. Preece as to why I referred in conclusion (1) to comparatively rapid cooling through the upper critical range being necessary to produce the granular type of fracture. In every case we did not obtain fracture type *E* with the dull grey transcrystalline facets unless the material had been oil-hardened and tempered after the overheating treatment. Therefore, it is the rapid cooling rate through the upper critical range, as Mr. Preece rightly concluded, which produces the relative strength of crystal and crystal boundary resulting in the particular type of fracture we associate with overheated material.

Regarding Dr. Jenkin's remark that I had not recorded the actual rate of cooling in asbestos in our experimental procedure, we took two extremes: Slow cooling as one, and oil-quenching as the other. Subsequently we determined the time–temperature graph for the asbestos cooling procedure, which proved very similar to that of Mr. Woolman and Mr. Kirkby. That may account for certain differences between the evidence of Mr. Preece and that of Mr. Woolman and my own.

With reference to the diffusion and precipitation hypotheses put forward, Figs. 5 and 9 in my paper, at magnifications of 800, show broad grain boundaries but with no marked outline, and certainly no evidence of incipient fusion, even with an overheating temperature of 1400° C. It is difficult, therefore, to consider a precipitation having taken place at a grain boundary and yet leaving a broad boundary with no marked line of demarcation. After oil-hardening and tempering, and again at a magnification of 800, the specimen in Fig. 14 shows a dark, broad line extending horizontally across the photograph,

but I do not think anyone would call that a sharp grain boundary or any form of precipitate. Also, as Mr. Preece has pointed out, the normal analysis of the material—carbon, silicon, manganese, sulphur, phosphorus, oxygen, and nitrogen—does not seem regularly to influence the phenomenon of overheating; what, therefore, is the basis of the precipitate? I think the diffusion theory of Mr. Preece and his colleagues is more acceptable, but, again, it is rather puzzling in one respect: Mr. Preece shows that he can get evidence of overheating in less than 5 min. and he subsequently indicates that up to 5 hr. there is no material difference. I should say that as diffusion is a function of time, for the longer time period of, say, 5 hr., the diffusion should be greater, and one would therefore expect greater signs of overheating on the fracture. Whilst that theory may prove quite sound and subsequently in line with my own suggestion of a possible phase change at the boundary, I think a lot more has to be done to prove what is happening at the boundaries.

There is another point in that connection. We have ample evidence that open-hearth steels, with higher non-metallics than basic electric steels, require a higher minimum overheating temperature to get the granular faceted fractures. If the precipitation hypothesis were correct, one would expect exactly the reverse, *i.e.*, the dirtier the steel, the more would it be prone to overheating. It may be that some future work will show that one particular type of non-metallic has an overriding influence and may account for the phenomenon.

Mr. Preece and his colleagues show quite clearly, I think, that the furnace atmosphere does not seem to matter very much, and Mr. Woolman and his colleague show that the same effects can be obtained in a vacuum. Mr. Merchant's statement does not agree with those findings; he inferred that a strongly oxidizing, turbulent atmosphere resulted in overheating at lower temperatures. I should like to suggest that a furnace which has a turbulent oxidizing atmosphere is one which would very easily result in local hot spots, and those hot spots might produce the overheated structure, whereas the actual general temperature in the furnace might be much lower than is indicated by those positions.

Now, turning to the question of resuscitation: In our paper we say that by re-oil-hardening and retempering it is possible to eliminate the overheated type of fracture unless it is too severe. A repetition of that treatment will again further remove the evidence of overheating. Several of the other workers have suggested temperatures of the order of 1100° C. and upwards. I quite agree that those temperatures appear to resuscitate the material, but I would point out that often a forging is heat-treated in the machined state very near to final dimensional requirements and very often it is impracticable to reheat to 1100° C. or over, in view of the possibility of distortion and decarburization of the surfaces.

It is very clear from all the work that a lot more must be done to determine why overheating takes place. All the experiments carried out so far show certain characteristics associated with grain-boundary weakness. Whilst they add to our knowledge, they are insufficient at the present time to show, or even to suggest, the mechanism of overheating.

Mr. Preece's paper, Mr. Woolman's paper, and my own, cover a considerable amount of common ground and in many cases the factors have only partially been elucidated. It would be better if such points were completely examined to show their significance or to eliminate them from any active part in the overheating mechanism. It appears to me that at the moment there is too much speculation on too little evidence, but the hypotheses put forward could be used as a basis for further work. I think that work should be done in collaboration, certain sections being allocated to the various investigators, rather than that each should formulate his own programme, often covering the same ground as other workers. In that connection, perhaps it would not be out of place to suggest that the British Iron and Steel Research Association be asked to participate in any future work on this subject.

Mr. J. Woolman (The Brown-Firth Research Laboratories, Sheffield): On p. 235 P of his paper Mr. Merchant outlined various aspects of the subject which were still obscure. In our work we have tried to answer some of those questions, as have Mr. Preece and his co-workers and Mr. Goodrich. For example, we have shown that different steels and, more particularly, steels made by different processes, may have widely different overheating susceptibilities, and it appears to us that the elements oxygen and sulphur are very important in this connection. We believe that furnace atmosphere has no influence or only a negligible one on the phenomenon. We have shown—I think fairly conclusively—that forging can affect the overheating temperature and in our experiments it had the apparent effect of raising the minimum overheating temperature some 75° or 100° C. We have also shown fairly conclusively, I think, that the method of steel manufacture is important, particularly in the deoxidation technique adopted, as also is the rate of cooling from the overheating temperature. We would like to emphasize that crystalline fractures or faceted fractures can be obtained with material which is not overheated and one can only judge on the nicked-fracture

test that a material has been overheated provided that it is put into a toughened condition, usually by hardening and tempering. Mr. Goodrich's paper may be taken as a warning against confusing large crystalline fractures with overheating and if this is remembered I think many of the apparent inconsistencies will disappear.

The actual cause of overheating is still very obscure. Mr. Preece will not go further than to say that it is due to some diffusion phenomena, either to or away from the grain boundaries. We cannot believe that diffusion away from the boundaries can explain the phenomena and we are therefore led to the opinion that it is some form of precipitation to the grain boundaries. We think most of our results support this view. Whatever the precipitate is, it must be one which has practically zero solubility at all temperatures below the minimum overheating temperature, with a fairly rapid rise of solubility above that temperature, so that only a very small content of the constituent need be present in the steel for the phenomenon to occur. One of the difficulties in this theory is that as the oxygen and sulphide increases, so does the minimum overheating temperature, which would appear to rule out these materials as possible precipitates, but it is hard to visualize what else they may be. In that connection I would refer you to the result of the experiment where we remelted material in a vacuum, and to the analyses on p. 277 P. It will be seen that as a result of vacuum melting there was very little change in carbon, there was a big drop in manganese and in sulphur, practically no change in phosphorus, and a big drop in oxygen, hydrogen, and nitrogen. Mr. Preece says there is little or no correlation with nitrogen as regards the minimum overheating temperature, but it seems to me that his plotted points show a definite trend with higher nitrogen contents towards a lower minimum overheating temperature. That would appear to be in the right direction, but it does not fit in with our conception that below the minimum overheating temperature the solubility of the precipitate must be very small indeed, because nitrogen has a fairly high solubility in iron; similarly, hydrogen has a fairly high solubility in iron; and so we are left with the elements manganese, sulphur, and oxygen. It is difficult to choose between oxygen and sulphur. We do not know their solubilities and I would be glad if anybody could tell me what they are. However, one might imagine that the solubility of sulphur would be less than that of oxygen, and therefore we incline slightly to the view that it may be sulphur. The fact that with increasing sulphur contents the overheating temperature is raised—and the same applies with increasing oxygen contents—may be due to the increasing quantity of the substance which is not in solution at the temperature—that is, the greater quantity of material present as inclusions and not in solution. It may be that these inclusions act as nuclei and that the precipitation takes place on them and not at the grain boundaries. In his remarks Mr. Preece said that he thought a white boundary which had a definite width suggested that it was not in agreement with the precipitation theory, but obviously the precipitate must come from a zone very close to the grain boundary, owing to the low solubility of the precipitate, whatever it is. Therefore, just as in the phenomenon of intercrystalline corrosion, it is just the material near the grain boundaries from which the precipitate comes.

Professor F. C. Thompson (University of Manchester): In our paper we have described what we did, the results obtained, and the explanation we offer for them. It would be a waste of time to amplify that, but there is one point which has emerged in private discussion, namely: What do we mean by the "indirect" effect of oxygen on the S curve? Oxygen may, of course, shift the curve of itself, but it is at any rate equally likely that the way in which it operates is indirect. Another element x—and your guess as to what x is will be as good as my own—may possibly shift the S curve to the right. If oxygen reduces the content of this hypothetical constituent it will *appear* to shift the curve to the left, although in actual fact the movement of the curve may be due not to oxygen itself but to this other element.

Considering the papers as a whole, it is abundantly clear that the overheating and burning of steel cannot be ascribed to any one element *per se*, and an explanation has to be looked for in a radically different direction. The precipitation theory of Mr. Woolman and Mr. Kirkby is in some ways very attractive and, I think, contains at any rate part of the truth, but the phenomena are so complex that it may very well be that no one explanation is adequate to explain the whole of the facts. The papers, however, do throw an enormous amount of light on the possible effect of gases and one may make out a very arguable case that there is now something like proof that such gases are one of the main causes of overheating and burning. Mr. Woolman has already drawn attention to the fact that the figures given by Mr. Preece and his co-workers in Fig. 5(d) show the very marked effect of nitrogen. If a curve is drawn downwards from the point 51, through 59 to 31, every single point, with the exception of steel 77, however the steel may have been made, falls below that line. There is, therefore, very strong reason for the belief that, other things being equal, as the nitrogen content is increased so is the tendency to burning increased. How do these gases work? I suggest that one

assumption, and one only, need be made: That there may be at the boundaries of the grains a greater solubility than in the crystal itself. Making that single assumption—and if time permitted I should be perfectly prepared to justify it—it seems to follow, and I am in complete agreement with Mr. Woolman on this point, that the evidence as a whole suggests that the reaction between FeO and carbon is the main contributary cause. It is not, however, the *average* content of oxygen, or whatever it may be, that matters; it is the concentration at the grain boundary. Consequently, it is not at all surprising that in many cases there is no apparent correlation between the element and the tendency to burning or overheating. If that is accepted, one has at once got an explanation of another fact. If in Fig. 5(*b*) of the paper by Mr. Preece and his co-workers a line is drawn from 79 to 46, and through 21 and 33, then, with the exception of one steel, 35, which lies just outside that zone, there is an absolute correlation between sulphur content and overheating. All the steels, irrespective of the method of manufacture, fall equally within that zone; therefore, sulphur seems to increase the overheating temperature. Now, sulphur is known to deoxidize steel and, presumably as a result of that, sulphur dioxide is formed. In the case of the bronzes, it is well known that sulphur dioxide has a detrimental effect, and one would, therefore, at first sight, expect it to have an equally detrimental effect on the steels. It is noteworthy, however, that the volume of sulphur dioxide produced by reaction with a given amount of FeO is only one-half of the volume of CO produced by the reaction of carbon with the same amount of FeO. The total volume of gas produced, therefore, is less—a fact which provides an explanation of the effect of the sulphur. Consequently, in seeking an explanation on these lines we are concerned with the oxygen content, the sulphur content, the nitrogen content, the hydrogen content, and, in fact, everything which is capable of producing a gas. The boundary concentration of gas will set up tensile stresses across these boundaries, and if those tensile stresses are sufficiently intense a permanent weakening is to be expected. There will therefore be every gradation between a normal material and one which has been utterly ruined, and no sharp line of demarcation can be expected.

This explanation can be used to explain, for instance, the effect of forging, since the area of the grain boundaries becomes a matter of fundamental importance. Now, it is not to be expected that very direct correlation between grain-sizes and overheating temperatures will be obtained from a haphazard series of steels of all sorts of compositions and methods of manufacture; but the point here is not that; it is the effect of grain-size in a *given* sample of a *particular* steel.

Dr. H. Sutton (Ministry of Supply): These papers refer to a trouble which, like hair-line cracking, happens to be closely associated with those periods in the world's history during which, as mentioned by Mr. Merchant in his paper, the production of forgings is greatly accelerated. The present time seems to be a very opportune one for careful consideration of the phenomenon. In this connection we are greatly helped by this very interesting set of papers, which provide a vast amount of information. On reading them, I was struck by the completeness and thoroughness of Austin's work in this field, which was done several years ago. To that work, I am glad to see, the authors have made fitting reference.

The excellent micrographs in these papers are a valuable aid to those of us who have occasionally to consider the significance of what is seen on fractures of overheated material.

An interesting point has been raised by Mr. Woolman and by Professor Thompson in relation to nitrogen content. It seemed to me that in Fig. 5(*d*) of the paper by Mr. Preece and his colleagues there was very clear evidence that nitrogen was something to watch rather closely; the bulk of the plots fall rather conveniently in biggish clumps.

The feature of the coarse grain structure which gives rise to anxiety, in my mind and in that of many of my colleagues connected with aircraft, is the influence on the performance of the parts. Professor Thompson has mentioned features which are of importance in this connection.

The effect on fatigue properties can, in some cases, be quite appreciable. It is difficult to avoid the impression that extensive troubles would have occurred with the use of some of the higher-alloy steels, such as *S*82, in the absence of the carburizing treatment. As mentioned by Mr. Merchant, the carburizing treatment results in appreciable improvement of the grain structure by reason of the effect of the thermal treatment involved, but there is a further effect in that it results *per se* in some improvement of the mechanical set-up of the core plus the carburized case, and it is well known that the existence of a carburized case on a piece of steel properly treated does give greatly enhanced fatigue performance.

From the point of view of the user, it may be that the effect of the overheated structure is to some extent masked by the hard case and its effect on the fatigue performance. It would be of interest to have the views of aero-engine metallurgists on that point.

One feature which interests me is that the overheated condition, if present in an advanced

degree, can be detected by modern methods of electro-magnetic inspection as used for crack detection. I would be very much interested to hear the experiences of those who have a knowledge of those methods.

Mr. J. HINDE (Bristol Aeroplane Co., Ltd., Bristol): During that period of the war when supplies were difficult, we at the Accrington aero-engine factory of the Bristol Aeroplane Co., Ltd., knew that overheating was suspected in a large number of components, and the evolution of a satisfactory inspection method was complicated by the local occurrence of overheating in individual components. Unfortunately, many components suspected of being overheated were in the more or less finished condition; obviously, with finished components a fracture test was impossible. Whilst some stampings had integral test-pieces attached to them, other stampings had not, and that imposed limitations on the fracture test. On the connecting rods, with which Accrington was most concerned, overheating invariably occurred at the end opposite to the integral test-piece, so that again the fracture test on the stampings involved could not be satisfactorily applied. In some instances burning could be detected by magnetic inspection but overheating could not. From experience the likely location of the overheating was reasonably well known, and the nitro-sulphuric etch was the method finally decided upon as our inspection method. The connecting rods were graded by this etch into grades *A*, *B*, and *C*, depending upon the extent and clarity of the boundaries thus revealed. Subsequently the grading was extended to *F*. The method was practised originally on finished components and was later extended to stampings. An effort had necessarily to be made to assess the significance of the overheating in relation to service conditions, and a decision had to be made as to what grade of overheating could be tolerated in a connecting rod which had to go into an engine and fly—that is, without any danger of premature failure. At Accrington it was found that the grade of overheating was not necessarily reflected in the routine mechanical properties. However, the effect upon fatigue properties, as discussed by Mr. Frith, was discovered.

The surface of finished rods was such that the nitro-sulphuric etch could be applied with little further preparation. On stampings, the affected end had to be surface-ground and shop-polished before the etch could be applied. The method, as you would expect, was laborious, but it was successfully organized and proved satisfactory. Many thousands of rods were examined and graded in this way. From one British source, of 11,000 stampings examined, some 300 were found to be burnt and about 2,000 overheated to grade *C* or worse. Grade *C* was that stage where a definite pattern of grain boundaries began to be revealed by the nitro-sulphuric etch; grades *D*, *E*, and *F* showed a thickening of the boundaries and a generally more definite pattern. From the same source, we examined some 6,000 finished rods and 1,500 were found to be overheated to about grade *C*. From two other British sources we examined many thousands of stampings and finished rods and found none to be overheated or burnt. Many thousands from an American source were examined, and some 20% of the stampings were found to be overheated to grade *C*; very few were worse than grade *C*, but of 3,000 finished components, only 67 were of grade *C*. The difference in the rejection rate between stampings and finished components served to indicate the variation in the degree of overheating from the outside to the centre of a section.

Experiments with hydrochloric acid pickling, which we saw demonstrated by Mr. Clary of the Ford Company, gave promising results, and it was intended to apply this method to all stampings in the Accrington engine factory as a routine inspection operation, the idea being to cut out the initial surface grinding and polishing, which was costly and relatively slow. The necessary equipment, however, was not installed in time to be put into production use before the turn of events in the war caused the high rate of production to be slowed down.

A considerable amount of work was involved in this production study of overheating, and some observations from our experience might be mentioned. If a fracture characteristic of overheating was obtained and we applied the nitro-sulphuric etch, we got a response equivalent to grade *C* or worse. On the other hand, if we took a sample that gave grade *C* or worse on the nitro-sulphuric etching and then fractured that sample, it did not necessarily follow that the fracture produced would give the facets taken as being indicative of overheating; that was found in many cases. Incidentally, the fracture samples had been hardened and tempered. We also examined many rods that had seen actual service, most of which had reached the overhaul period and were available for our nitro-sulphuric etch. We found some approaching grade *C* but the majority of the rods examined were not overheated to that extent. I would like to mention that one component, not a connecting rod but in *S*90 material and stressed very differently, had run for 240 hr. quite satisfactorily. It was taken from an engine stripped down for other reasons. Out of interest, a fracture test was made, and on that fracture test that component showed as bad an example of overheating as indicated by a

faceted fracture as I have ever seen. We experienced failures of rods which could be traced to burning, but in my experience no failure could be attributed to overheating.

Many other methods of etching were tried, but only one gave results comparable to the nitro-sulphuric etch; that was a 2% solution of sulphuric acid, using the electrolytic etching method with a 10 V., A.C. supply. This method produced black boundaries rather similar to the nitro-sulphuric etch, but it could not, for obvious reasons, be applied very easily to production components.

I believe Mr. Preece refers to white boundaries as distinct from the more general black boundaries. We put one end of the shank of a connecting rod into a blacksmith's hearth and turned on the heat furiously until definite melting occurred and also burning at that end, hoping in that way to get a gradation from burning to overheating. Burning was apparent visually and was indicated more clearly by magnetic examination. On applying the nitro-sulphuric etch to the affected end, white boundaries were apparent. Of the many thousands of rods examined, we only found this white boundary effect on one, and that was a rod which had seen service; it was of American origin and had run for 320 hr. quite satisfactorily.

Mr. P. Frith (Bristol Aeroplane Co., Ltd., Bristol) (read in his absence): During the last four years a considerable number of tests have been carried out in the "Bristol" laboratory on the effect of overheating on the fatigue properties of nickel–chromium steels; these tests were initiated to assist the design and inspection departments in obtaining satisfactory standards for acceptance. When the problem was first submitted to the laboratory, it was found that a considerable number of finished-machined components had varying degrees of overheating, and therefore it was necessary to grade the components by some non-destructive test. Although it was realized that the nitro-sulphuric acid etch, even under controlled conditions, had its limitations, it was considered that this test was the most suitable to use, in view of the components being in the finished-machined condition.

This overheating problem affected various components, but it was thought that if the fatigue tests were carried out on a steel that had been air-hardened and tempered to not less than 100·0 tons/sq. in., maximum tensile strength, then the reduction in the fatigue properties due to various amounts of overheating obtained with this steel, could quite safely be applied to lower-tensile steels.

The first series of fatigue tests were carried out in the Avery–Schenck push–pull fatigue machine on finished-machined articulated rods, air-hardened and tempered to not less than 100·0 tons/sq. in., maximum tensile strength. (The area of the wrist-pin or gudgeon-pin eyes at the position of the fatigue fractures was approximately 0·5 sq. in.) On completion of the test on each rod a micro-section was prepared from the commencement of the fatigue fracture and, after etching with nitro-sulphuric acid under controlled conditions, photographs were obtained at a magnification of 100. It was considered necessary to grade the degree of overheating from A to C, as shown in Fig. D. The results of the fatigue tests are shown in Fig. A.

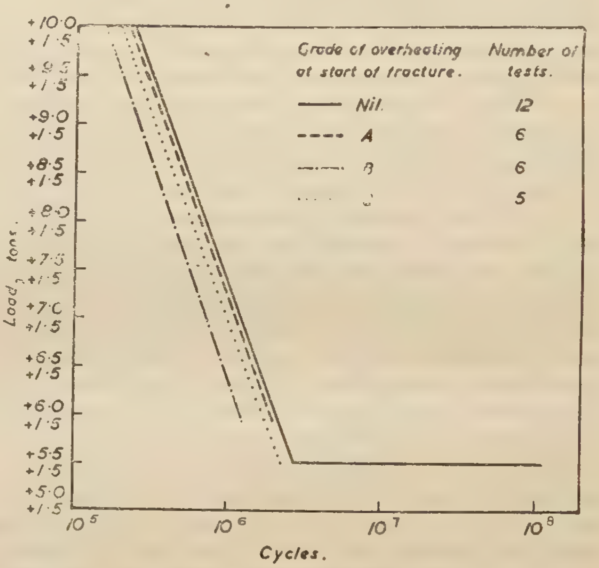


Fig. A.—Results of Fatigue Tests (Avery–Schenck push–pull machine) on finished-machined articulated rods of nickel–chromium steel ($S28$) in the air-hardened and tempered condition. (Maximum tensile stress not less than 100 tons/sq. in.)

From these fatigue tests it appeared that some degree of overheating could be permitted on articulated rods, especially as the nitro-sulphuric acid etch would be carried out on the outside surface of the wrist-pin or gudgeon-pin eyes, whilst the fatigue fractures commenced on the inside surface of the eyes. In general it was found that the degree of overheating was greater on the outside than on the inside surface of the eyes. The actual decrease in the fatigue limit due to an overheated structure was not determined on this series of tests, because it was found that the rods which were unbroken after the test did not have an overheated structure. It was also found on this first series of tests that the fatigue properties were slightly inferior for grade B overheated structure than for grade C overheated structure; this was most likely due to the fact that the rods tested were from various batches, and therefore

other variables apart from overheating slightly affected the results.

However, although the first series of tests enabled a temporary satisfactory standard to be obtained for acceptance purposes, it was felt that the effect of greater amounts of overheating on the fatigue properties should be determined, and it was decided to carry out this second series of tests on sections cut from articulated-rod forgings, using reversed bending stresses. A number of forgings which revealed burning on the outside

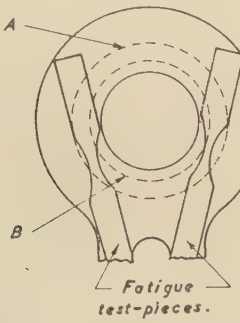


Fig. B.—Method of Sectioning Articulated Rods, showing approximate position of (*A*) gudgeon-pin bore and (*B*) wrist-pin bore, of finished-machined articulated rod.

surface by a magnaflux examination were chosen for this investigation, and the sections were cut close to and away from the "burnt" areas, rough-machined, heat-treated, and then finished-machined. The method of sectioning is shown in Fig. B. On completion of the fatigue tests a microsection was prepared from the commencement of the fatigue fracture, as for the first series of tests on the articulated rods and, after etching with nitro-sulphuric acid under controlled conditions, photographs were obtained at a magnification of 100, and the degree of overheating was graded from *C* to *F* as shown in Fig. E. In addition to the micro-examination of the test-pieces on completion of the tests, it was decided to carry out a macro-examination, which showed that the fatigue properties had not been affected by any transverse grain flow. The results of the fatigue tests are shown in Fig. C. From these stress–endurance curves it was possible to determine the endurance limits based on 5×10^7 cycles, with and without an overheated structure, and the values obtained are presented below:

(1) *Specimens not Overheated.*

Test-Pieces Machined from—	Estimated Endurance Limit on a Basis of 5×10^7 Cycles, tons/sq. in.	Mean Value, tons/sq. in.
1-in. dia. bar .	$\pm 45 \cdot 5$	$\pm 46 \cdot 4$
5-in. square bar .	$\pm 47 \cdot 4$	

(2) *Specimens Overheated* (*Machined from Articulated Rods*).

Grade of Overheating.	Estimated Endurance Limit on a Basis of 5×10^7 Cycles, tons/sq. in.	Approx. Decrease in Endurance Limit due to Overheated Structure,* %.
C	$\pm 44 \cdot 3$	4·5
D	$\pm 42 \cdot 3$	8·8
E	$\pm 39 \cdot 1$	15·8
F	$\pm 36 \cdot 0$	22·4

* Calculated from the mean value of $\pm 46 \cdot 4$ tons/sq. in. obtained for the specimens not overheated.

Eleven sections were cut near to where burning was detected on the outside surface by the magnaflux examination, but no evidence of "burning" was detected at the commencement of the fatigue fracture on the specimens machined from these sections. This was no doubt due to the stressed section of the fatigue test-pieces being machined approximately 0·4 in. below the surface of the forging. The degree of overheating on the stressed section of these eleven test-pieces varied

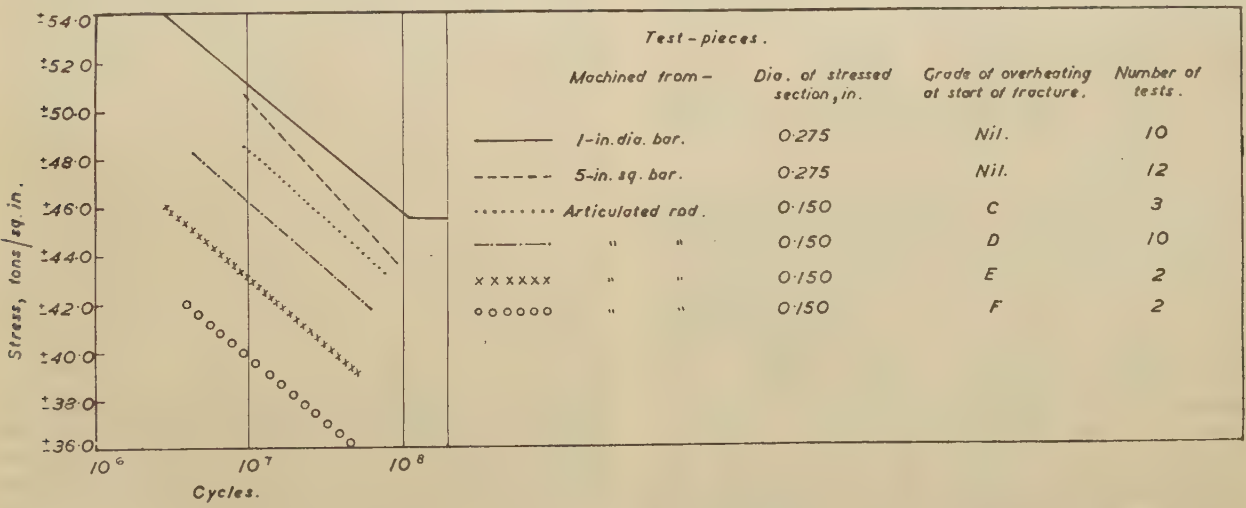


Fig. C.—Results of Fatigue Tests (Reversed Bending Stresses) on a nickel–chromium steel (*S*28) in the air-hardened and tempered condition. (Maximum tensile stress not less than 100 tons/sq. in.)

over grades C to F, and only two specimens had an overheated structure of grade E or F at the commencement of the fatigue fracture. Therefore the stress–endurance curves for these grades of overheating were only approximate but, as all the four specimens showed that this amount of overheating considerably reduced the fatigue properties, and, as previously stated, the tests were carried out to determine suitable standards for acceptance purposes, it was decided not to carry out any more tests, nor to try and obtain further results with grades E and F of overheating.

From an examination of the test-results it was observed that when the sections were cut away from the areas which revealed " burning " on the outside surface of the forging by the magnaflux examination, the grade of overheating at the commencement of the fatigue fractures was either C or D. The stressed section of the fatigue specimens was machined from approximately the same position in the forging as the inside surface of the wrist-pin or gudgeon-pin eye of a finished-machined articulated rod, where the fatigue fractures usually occur. Therefore it appeared from these fatigue tests that, if articulated-rod forgings were magnafluxed prior to machining, and all rods which did not reveal " burning " were accepted, then it was possible for the finished-machined rods to have a grade D overheated structure inside the wrist-pin or gudgeon-pin eye, with a reduction in the fatigue properties of approximately 8·8%.

Professor G. Wesley Austin, O.B.E. (Cambridge University): May I congratulate each of the investigators on the new knowledge contributed to this very complex problem, and thank Dr. Sutton for the kind remarks he made about my own work? Actually it was not very good; but a problem was pressing and it had to be dealt with. I set myself three questions: (1) How could the defect be detected? (2) What was its effect on the mechanical properties? (3) What was the actual nature or mechanism of the defect?

As regards the detection of the defect, a series of failures of pressure containers was encountered. The containers were under complex stress, two-dimensional tension, and when we examined the origin of the failure we found the faceted structure, which we regarded as a factor contributing to the failure. The next question was whether we could find anything in the material or the microstructure which corresponded with the facets? I had a long talk with the late Dr. Dickinson. We discussed various reagents and he suggested that I should try a strongly acid reagent. Mr. Howarth actually proposed the reagent which, quite wrongly, has been called by my name. We etched many samples from the origin of the fracture with this reagent and found polygonal grains outlined; we concluded that this outline corresponded with the facets observed in the fractures. We looked for other tests, because it was very difficult to decide whether to reject all material from the same casts; but we did not get very far. We attempted to examine turnings from the forgings, but had very little success with that. We never thought of the magnaflux method. If the magnaflux method detects this defect, surely there must be a discontinuity. I think this fact may lead the investigation further. That was as far as we got with the detection of the defect.

The next problem was the examination of the mechanical properties. I will briefly repeat what Professor Thompson has said. My own feeling about the load–extension curve is this: In a homogeneous steel in a longitudinal test, the necking continues for a very long way after the maximum load, so we get excellent figures for reduction of area and larger elongation because of the proportion of the total elongation that is due to necking. If there is any gross defect in the steel, or if we pass from a longitudinal test to a transverse test, the load–extension curve is arrested earlier. In the case of the burnt steels, as the burning increases, the load–extension curve is arrested earlier. This, I think, perhaps throws some light on the fatigue results. All sorts of formulæ have been proposed to correlate fatigue strength with tensile strength. First of all, the fatigue strength was expected to be half the maximum load, and then the yield point was brought into it. Some formulæ have been proposed in which the reduction of area is a factor. I think in this part of the test the stresses are very complex and any material which shows an earlier arrest of the tensile curve in this range is likely to show premature failure under combined stresses. Eventually there may thus be some connection between the earlier arrest of the load–extension curve and the fatigue results. If the burning is bad, maximum load is not reached, and if it is really bad the yield point even is not attained.

As to the cause of the defect, I feel I cannot give any more information, but there is a great deal of new work in the papers. If the recent work on fatigue is correlated, I think a definite advance will be made on the servicibility of the material. As regards the cause of the defect, I feel I was perhaps quite wrong in attributing it to the melting of inclusions which flowed by capillarity round the existing boundaries at the time the defect occurred; that does not seem to be the opinion of any of the present investigators.

Professor P. G. Bastien (Messrs. Schneider & Cie., Paris): Dr. Jenkin has given a most interesting

review of the question, to which I should like to make a few additional remarks.

In the case of defects which may arise in steel on exposure to high temperatures it is usual to distinguish between overheating (or excessive austenitic grain growth) and burning (or incipient fusion). However, in our opinion, this distinction simplifies the question too much, for there are various degrees of overheating and burning, and even a gradual transition between these stages seems to be possible, so that they are difficult to identify, and the conditions of the transitions between them cannot be readily established, since they depend on :

(*a*) The chemical composition of the steel,

(*b*) the homogeneity of the part (dendritic segregation being important—a point which has perhaps not been stressed sufficiently),

(*c*) the temperature reached and the holding time at that temperature, and

(*d*) the cooling rate after heating, which governs the influence of the heterogeneity developed when on decomposition of austenite the steel reaches a two-phase state (segregation of ferrite and cementite on cooling, especially in certain steels with inclusions).

Regarding overheating it is possible to distinguish between :

(*a*) Ordinary austenitic grain growth with a corresponding coarsening of the microstructure obtained on cooling; in this case restoration by refining-annealing (heating above the Ac_3 temperature followed by sufficiently rapid cooling) is not difficult.

(*b*) Coarsening of the austenitic grains accompanied by a modification of the cohesive properties of the grain boundaries and the formation of brittle fractures with large intercrystalline facets; this is the type of overheating dealt with in the papers presented, and its elimination by heat-treatment of the part affected can be very difficult.

Similarly, if one holds the view that burning may occur from the very beginning of fusion even of traces of metal—for instance, in the form of a liquid capillary film at certain grain boundaries—it is possible, according to Portevin,* to distinguish the following degrees in the phenomenon :

(*a*) Incipient fusion and separation of the liquid rich in impurities and carbon; owing to the low rate of diffusion strings and islets of cementite are formed on cooling and brittleness arises; this brittleness can be reduced, at least to a certain extent, by homogenizing and other restoring treatments.

(*b*) Incipient fusion, separation of liquid containing impurities and carbon, and liberation of gases causing the formation of voids; this failure can be corrected to some extent only if one avails oneself of the possibility of forging the piece subsequently.

(*c*) Incipient fusion as before but more pronounced and combined with intergranular loosening and oxidation in the grain boundaries; this process is irreversible and no remedy is possible. In practice, by the way, this is usually the state described as "burnt steel."

The transition between these various stages is gradual, and it is often difficult to distinguish, for instance, between the second degree of overheating and the first degree of burning.

In the following we will consider only the type of overheating which in steel correctly quenched and tempered is characterized by the formation of fractures with large facets, and I am summarizing the views based on cases experienced in practice as well as on overheating experiments devised and carried out at the Creusot works in France. Largely in agreement with the conclusions of the interesting papers presented to-day, we have found the following points :

(1) This type of overheating is particularly well shown up by the formation of fractures with large facets in the notched-bar impact test, especially on testing in the transverse direction.

(2) The micro-examination is less conclusive and does sometimes not reveal anything—not even with special etching reagents on the nitric-acid or nitric-acid-plus sulphuric-acid basis (the use of which fairly frequently causes irregular and not very satisfactory results—especially when it is desired to reveal the grain boundaries of the austenitic structure as prevailing at the moment of overheating.

(3) In treated pieces this type of overheating has little effect on the breaking strength and the elastic limit as found in the tensile test; but, on the other hand, it reduces the elongation at fracture and the impact strength in transverse tests.

(4) The tendency of a steel to yield fractures with large facets on overheating is governed by its composition and its manufacture. The most typical cases encountered at the Creusot works were chromium-nickel-molybdenum steels produced in the acid electric furnace, so that we have arrived at the conclusion that these

* A. Portevin, *Aciers Spéciaux, Métaux et Alliages*, 1932, vol. 7, pp. 242–256, 282–297, 318–328, 396–412; 1933 vol. 8, pp. 2–18, 203–222, and 231.

steels—which, incidentally, are particularly clean with regard to inclusions and are made up of austenite grains growing readily—are particularly prone to this type of failure, which is in accordance with the conclusions of Mr. Preece and his colleagues.

(5) It seems very likely to us that there is a relationship between overheated fractures with large facets and the austenitic grain growth during the holding at very high temperatures.

(6) On the other hand, an effect of the rate of cooling—although to be expected since diffusion phenomena are involved—is not so clearly obvious. Incidentally, Mr. Goodrich indicates that comparatively rapid cooling in the upper critical zone is necessary for the development of the type of granular fracture in question, whilst Mr. Woolman and Mr. Kirkby are of the opinion that a high cooling rate tends to suppress the formation of facets.

It would be most important to establish the effect of the rate of cooling; for this might throw light on the precipitation or the intergranular accumulation of an element or a phase at the temperature of overheating, *i.e.*, a heterogeneity which with rapid subsequent cooling would not have the time to become distributed more evenly.

Finally, I should like to draw attention to the extraordinary perseverence of overheated fractures with facets, which is observed in certain cases. We observed this in a very pronounced form in forgings of two chromium–nickel–molybdenum steels which had been produced in the electric furnace and had the following compositions :

Carbon, %.	Silicon, %.	Manganese, %.	Nickel, %.	Chromium, %.	Molybdenum, %.
0·250	0·300	0·550	2·00	0·65	0·275
0·300	0·300	0·550	3·00	1·00	0·275

In transverse mechanical tests after heat-treatment consisting of quenching in water or oil with subsequent tempering at 650° C., we frequently obtained unsatisfactory values of the elongation, the reduction of area, and the impact strength, together with fractures showing large facets (Fig. F). Restoring treatments were tried on samples of steels presenting this type of fracture, the treatment consisting of reheating to a high temperature (1200°, 1150°, or 1025° C., depending on the individual case) and holding for 30 min., followed by air-cooling down to 200° C. and two or three more reheating treatments at intermediate temperatures before heating to the hardening temperature of 830° C. and tempering at 650° C. In no case did the homogenizing and restoring treatments, which usually are very effective, cause the disappearance of the overheating fractures.

The micro-examination of test-pieces with fine, as well as those with coarse, fractures * did not reveal any differences, a normal sorbitic structure being obtained with the classical etching reagents (Fig. G), and with the special sulphuric acid and sulphuric-acid-plus-nitric-acid reagents a structure free from white spots, inhomogeneities, and grain boundaries (Figs. H and I). X-ray diffraction diagrams were not affected by the appearance of the fractures either.

By heating above 1350° C. it has been found possible to produce on these steels fractures with large facets, the number as well as the dimensions of which increase with the holding time.

In conclusion we might say that even though the phenomenon of overheating leading to faceted fractures is known in its essential features there are still many details to explore concerning the various physico-chemical mechanisms involved. In accordance with Mr. Merchant's conclusions, we think that the development of more refined metallographic polishing and etching techniques allowing of the reliable identification at room temperature of the grain boundaries in the austenitic structure formed at high temperature would be most desirable.

I wish to congratulate the authors of the papers presented to-day, which form an important contribution to a subject the details of which are little known as yet.

Mr. E. H. Bucknall (The Mond Nickel Co., Ltd.): At a certain stage in our knowledge of fatigue failures it was quite common that those interested in the matter, but not perhaps well-informed, referred to metals as having crystallized, because of the characteristics of the failure. I wonder whether at the present time we are not too eager to associate the faceted appearance of a fracture with a supposed intercrystalline course of the cracking. Although I have probably seen fewer examples than many people here, I am quite certain that I have seen examples where the faceted structure was on at least five to ten times the scale of the actual austenite grain-size and have noticed cases where the cracking was by no means always intercrystalline. I feel that Messrs. Woolman and Kirkby must have had the same experience, because in their concluding remarks they say :

> " Further, this constituent is already present in steels as cast, and with a sufficiently high temperature and a correct rate of cooling, a critical concentration of the constituent is precipitated at the austenite boundaries existing

* The overheated test-pieces were subjected to a complete heat-treatment after overheating, in that they were reheated to 850° C. and air-cooled, followed by oil-quenching from 830° C. and tempering at 650° C.

at that temperature. This concentration results in a series of interruptions of the crack induced in the usual nicked-fracture test, giving rise to the well-known appearance of the faceted fracture."

Messrs. Woolman and Kirkby then go on to hypothesize on the nature of precipitate responsible. I find it rather difficult to put myself into a frame of mind where I am prepared to throw on one side what seems to me to be the obvious explanation—that overheating is produced as soon as that temperature range is entered in which δ ferrite begins to appear. It is, of course, more than possible that Messrs. Woolman and Kirkby have unpublished information at their disposal with regard to the location of that temperature for the more complex types of low-alloy steels. If they have such information, I think we should plead with them for its publication. If no such information is available, we should press forward as energetically as possible to get that type of information.

When precipitation of δ ferrite commences, one may well have general precipitation within the grains, but there would be a preferential precipitation round the grains, giving rise to an impoverished boundary area, which would give the etching characteristics mentioned by several of the authors. Superimposed on this, I feel one has to have a second stage, in which either the residual material in the body of the grains or the impoverished zone round the grain boundaries is greatly impaired in its impact properties. Mr. Goodrich draws attention to the fact that tempering has to be above 400° C. to give rise to the faceted structure, and the results of Mr. Preece and his colleagues confirm that, except in the case of the steel of highest molybdenum content examined. It seems that we are dealing here with something akin either to the Izod trough or to temper-brittleness in one or other of the segregated areas developed in the steel at the overheating temperature. According to this view, the effects of slow cooling are, first, partial homogenization of that heterogeneous structure, and, later on, a tendency towards reduction of the impact properties of the structure as left after the first cooling stage.

Professor Thompson and Professor Wesley Austin have referred to the desirability of obtaining the true stress–strain curve of overheated material. I am inclined to feel, however, that unless overheating is absolutely general, it is a physical impossibility to determine the true breaking strain of affected material, because, where overheating is not absolutely general, there will inevitably be some areas of premature fracture within the area of a test-piece; this will affect the axial conditions of loading, and in any case reduce the actual area bearing the strain below the measured cross-sectional area of the test-piece.

The recent work of Professor Thompson and Professor Stanton has interested me a great deal. I am somewhat surprised to find them on this occasion leaving the question of the movement of the S curve by the burning treatment rather at the stage of a hypothesis. I feel that they could have resolved the matter completely by examining a second steel with an alloy content rendering it sufficiently slow transforming to enable them to record fully its transformation characteristics in the dilatometer instead of relying on inference from structures arising from transformation which had occurred above the quenching-bath temperature.

Mr. J. D. Latta (Scottish Stamping & Engineering Co., Ltd.): I do not know very much about the overheating of steel but I do know that it affects the drop-forgings I have to make.

I have read through these papers with great interest and I appreciate the great amount of technical work involved, but it does seem to me that no solution from the drop-forger's point of view has been found. It is still not possible to determine accurately whether or not a forging is overheated.

I know that Professor Wesley Austin and other experts agree with me when I say that it is not really possible to know whether or not a forging is overheated without internally destroying it. In this present age it should be possible by some means or another to determine accurately whether or not a forging is overheated to a detrimental extent without destroying it, and I can only hope that all you gentlemen, particularly those who wrote these papers, will persevere with your experiments until eventually a testing process is evolved which will enable us to rapidly and economically test our forgings with 100% accuracy.

When I read these papers my ideas were confirmed that the actual overheating could happen to the steel in various stages. A drop-forger could fairly easily overheat thoroughly a piece of steel in a forging furnace. He could even do it in a furnace with automatic temperature control, simply because the steel was in a particular state when it came into the drop-forge and was very susceptible to overheating. I am not really competent to go very deeply into the reasons for this but I am interested in encouraging, if possible, some system of inspection-testing that will enable the drop-forger to be sure that the forgings he sends out are in perfect condition.

I listened with interest to Mr. Hinde's experiences with connecting rods, and I was interested to hear that one component—not a connecting rod—taken from an engine, that had done some

240 hr. had been found to be badly overheated when tested by the fracture test, and in such a condition that, if it had been discovered before, it would not have been allowed to go into the engine; yet it had given good service in this engine. This convinces me that we do not really know very much yet about non-destructive tests for overheating.

Dr. H. O'Neill (London, Midland and Scottish Railway Co.): I would like to revive the nitrogen bogey—though Professor Thompson has forestalled me. I think the evidence contained in the papers, particularly those of Mr. Preece (p. 246 P and Table III.) and Mr. Woolman (Table II. and p. 277 P), indicates that burning depends on, or is associated with, the nitrogen content; the lower the nitrogen content, the less the liability to overheating or burning. I am, therefore, surprised by the statement on p. 246 P of Mr. Preece's paper that no relationship is apparent between nitrogen content and overheating temperature.

In connection with grain-growth studies of steel, British metallurgists always seem to have been pre-occupied with oxygen, whereas most of the German metallurgists have attached importance to nitrogen. Houdremont, in particular, considers that the grain-boundary-restriction effect is associated with a constituent high in nitrogen. It was that fact which made me look into these papers for any evidence for nitrogen and I think that it is there.

In my own work I have chiefly met overheating and burning effects in connection with the flash welding of low-carbon steels. The evidence in the papers shows that the trouble may vary from cast to cast, and the supervisors in one of our flash-welding shops have reached the same conclusion. They have devised a test whereby the bars of mild steel—always of the open-hearth variety—are flash welded and then rapidly bent whilst in the hot condition. The workmen say that in this way they can differentiate between casts of steel. Welds of low strength sometimes reveal a very slight burning effect to one side of the plane of welding. I therefore hope that some attention will be devoted to plain carbon steels in future, for the present papers are chiefly devoted to high-alloy steels.

On p. 253 P of his paper Mr. Preece mentions that he has difficulty in making hardness tests at the grain boundaries. I suggest that if tests by "micro-indentation" with a 50-g. load can be made on some of the boundary fracture facets he may be able to confirm or refute the indications of boundary hardness which he mentions. Finally, from the steel purchaser's point of view, as distinct from that of the steelmaker, I must confess there is a delightful vagueness about the present papers and about the terms "overheating" and "burning."

Dr. G. B. Waterhouse (Professor Emeritus of the Massachusetts Institute of Technology): Early in February I was in Cleveland, Ohio, where we had the first Convention of the American Society for Metals since the war started. At that Convention a very interesting paper was presented by Messrs. Jominy and Strohm. Jominy, who is known to all of you by name, is connected with the Chrysler Research Laboratories and is interested in the manufacture of drop-forgings. Strohm at that time was with the Timkin Company of Ohio, who are makers of high-grade steels. Those gentlemen presented a paper on this subject, and I am rather surprised that none of the authors of these papers has mentioned it. However, perhaps there has not been time for the paper to get here. I hope that all the authors will read that very interesting paper by Jominy and Strohm on this subject of the facets found in tests from drop-forgings made from certain steels. My recollection is a little hazy, but I think the main emphasis was on the prevention of that type of failure. I think they found that by very careful regulation of the soaking-pit temperatures, in the first place, then, later on, of the rolling temperatures, and, later on still, of the forging temperatures, this type of failure could very largely by prevented. I must admit that, to my recollection, they did not go into the question of whether it was caused by nitrogen, the separation of gases, or similar things, but I remember very clearly that they were very sure that by careful temperature regulation this type of failure could very largely be prevented.

Professor Bastien and I think a good deal alike. I think that when you get up beyond the zone of the solidus you get into the zone of burning; you get incipient fusion and there is nothing much you can do about it. The steel has been ruined and should be scrapped. On the other hand, until you get beyond the solidus line, you are still within the range of overheating, and then, by careful heat-treatment, you can do away with the bad effect that has been produced. That does not seem to be in accordance with the teaching of these various papers. I rather think these authors feel that the overheating has caused some action at the grain boundaries which cannot be overcome by subsequent heat-treatment, but, as I have not yet had time to study the papers with care, I may be wrong in that.

Mr. H. A. Whiteley (Messrs. Faulkners, Ltd., Colnbrook, Bucks): I was associated with Mr. Merchant in the early stages of the work, which started in 1941, largely as a result of very considerable rejections for what at that time we

considered were not legitimate reasons. Subsequently, we were partly converted, but I do not think that all drop-forgers are wholly converted even now.

I congratulate the authors on lighting up some very dark places in this problem of overheating. The phenomenon of overheating has been with us, to my certain knowledge, since about 1920. It lapsed somewhat in the period between the wars but it reappeared in about 1941, and to those associated with inspection and metallurgical control its rapid appearance and disappearance in a works is a serious problem. Unfortunately, owing to the pressure of war conditions, drop-forgers have had very little time to do anything but scratch the surface of the problem. That is what Mr. Merchant started to do in 1941, fully realizing that owing to the shortage of skilled metallurgical observers and workers we should not travel far along the road. Nevertheless, this group of papers does represent a very notable advance, and I hope that the problem will not be put back into cold storage now the war is over, as it was after the last war. In any case, I do not think the engineers will allow us to do that, because they demand ever-increasing physical properties and ever-increasing reliability from the forgings we produce.

As a drop-forger, I rejoice in the large measure of agreement which the papers show on certain points, and I feel sure we shall get more agreement when the various investigators return and consider the points which have been brought forward by Dr. Jenkin and other contributors to the discussion. Especially am I impressed by the idea of suppressing or removing the appearance of overheating by slow cooling from high temperatures. I have experiments in hand to see how far it is reproducible in works practice. We await, from Mr. Preece and his fellow investigators, the results of slow cooling on the physical properties after more considerable degrees of overheating than we have had described so far. I personally would like to see more evidence of the influence on the fatigue values.

At the same time I should like to draw attention to the fact that, although at present overheating is detected by means of fracture tests, the attachment of fracture test-pieces to forgings is a matter calling for the closest co-operation between the drop-forger and the customer. As has been pointed out, the test-piece may be satisfactory whereas the forging may be overheated. Non-destructive tests are required, but the only such test at the moment is the "crozzling" referred to in Mr. Merchant's paper. Firms select drop-forgings for acceptability or rejection, at the moment, mainly on the first operation of pickling in boiling hydrochloric acid which produces this "crozzling" on the skin. It is appreciated both by inspection departments and by the drop-forgers that this is not conclusive, but that so far it is the only non-destructive test we have on raw forgings. When the forgings are machined, we can apply magnetic methods but those methods, I think, only reveal burning and will not detect overheating.

I agree about the rapidity of grain growth. From my own experiments, it is extremely rapid.

As regards standard fractures, under the stress of war conditions we had to provide some guide to the people who judged the fractures. They were not fully trained metallurgists; indeed, some of them had no metallurgical experience at all. Therefore we provided them with a set of six or eight fractures as guides. Although we subsequently found that the standards did not agree for each cast of steel, the results were, in the main, satisfactory.

With regard to oxide films, of the large number examined quite enough were coloured to make Merchant and myself say that coloured oxide films occur on certain fractures.

I also agree that a furnace with a turbulent atmosphere may have local hot spots which cannot readily be detected. That point will have to be watched very carefully by drop-forgers.

With regard to the paper by Jominy and Strohm, I think it is true to say that their remarks and observations do not altogether coincide with those we have had presented to us in the present papers.

Mr. W. E. Cooper (The Fairey Aviation Co., Ltd., Hayes, Middlesex): This subject was of considerable concern to me some years ago when, as Chairman of the War Materials Committee of the aircraft industry, I was involved in the serious outbreak of overheating and burning of steel forgings, which may have lead to serious consequences in the war period if it had not been checked. Together with my colleagues both in the industry and in the Ministry of Aircraft Production, I had to recruit available assistance from drop-forgers and steelmakers, through the Iron and Steel Control organization. Several aircraft firms energetically conducted investigations to assist the immediate situation, and large-scale fracture and etch tests were carried out on tens of thousands of components; while for certain drop-stampings a maximum forging temperature of 1250° C. had to be stipulated. The steelmakers, through the Technical Advisory Committee, were unable to accede to our request for recommended maximum forging temperatures for our aircraft steels, an inability which frankly surprised most of us, in view of the fact that American standard references contained recommendations on temperature ranges. In any case, temperature control of forging furnaces would have taken a considerable

time to effect. Subsequently, at a meeting of a Joint Central Advisory Committee that was set up, the steel industry undertook to have the subject thoroughly investigated to produce definite practical recommendations for the benefit of both drop-forgers and aircraft firms.

When, therefore, it was recently announced that a general discussion on overheating of steel was to be held, one looked forward to acquiring some material advance in useful knowledge, which might have been obtained in the last four years. Perusal of the papers submitted revealed (excepting that by Preece and his co-workers) that there was nothing new of practical value or application to comfort or assist those affected by the 1942–43 epidemic of overheating and burning of drop-forgings. Very much of the general knowledge repeated in the present contributions was well known to those closely connected with the affected aircraft forgings in 1942 and one was inclined to ask: "Why this premature display?" Certainly, one paper shows that a start had been made to pursue fundamental causes and effects, but here again only a "progress report" could be presented. It was now very interesting to infer from Preece's paper that temperature was the main factor; and that furnace atmosphere was not influential, thus disposing of one of the factors put forward by the steelmakers four years ago. Surely, a symposium on this important subject should have been deferred to a later date, when the fabrication and user industries could have acquired some practical benefit and solution to their problems.

Most of the papers indicated:

That overheating and burning was a transitional phenomenon, accompanied by microstructural effects, peculiarly revealed by the H_2SO_4–HNO_3 etch, and by gradual changes in the fracture appearance.

That mechanical properties were progressively affected, particularly impact and ductility; and that early stages of overheating could be eliminated by thermal treatment, later stages by hot-working only and, finally, really burned steel was unrestorable.

That electric-furnace steel appeared more susceptible to overheating than open-hearth grades; and that generally speaking with many steels the trouble appeared to commence above a temperature of 1250° C.

From our aircraft-industry reports available in 1942, all these and much other data were available, but in Sheffield we were assured that this subject was extremely involved, necessitating the steelmakers' specialistic researches to provide the practical solution to the problem for both drop-forgers and aircraft firms. Four years have elapsed since the troubles and we are now presented with what is largely a repetition of 1942 aircraft-industry knowledge.

Dr. W. J. Wrażej (Imperial College of Science and Technology, London): The results reported by the various authors are very interesting and I am convinced that they will be of great value in practice. The features described are not unfamiliar to me; in 1939 I submitted a note to *Hutnik* (the Polish metallurgical journal) on the results I had obtained with steels of similar compositions used for aircraft parts (connecting rods). Owing to the outbreak of the war this could not be published.

As demanded by the inspection authorities, each of these connecting rods was provided with a square end-piece for impact testing as well as fracture examination. In the beginning the types of fracture shown by the authors were frequently observed. Since the coarse-grained structure obtained was thought to be due to overheating, great care was subsequently taken not to exceed a temperature of 1200° C. However, despite this precaution the formation of a coarse-grained structure could not always be prevented.

As is well known, a critical degree of forging or critical heating, or even forging quite lightly in the critical temperature range, may cause excessive grain growth in soft steels; and, accordingly, the failures could be avoided by choosing a suitable heating and forging technique. The attempt was also made to apply a second heat-treatment after normalizing at over 1000° C. In this way failures were avoided and the appearance of the fractures improved, the previous transcrystalline or intercrystalline facets (more frequently the latter) being no longer visible.

From a specimen the fracture of which showed intercrystalline facets two flat samples were cut of a thickness of about 2 mm., *i.e.*, a thickness not exceeding the grain-size. These samples were used for determining the tensile strength. It might have been expected that the material would break down into separate grains on slight extension; however, this did not happen and the individual grains could not even be recognized on a polished surface after extension, which leads to the assumption that the grain boundaries were strong and that the coarsening of the grains could not be due merely to overheating.

As far as I remember, the minimum tensile strength demanded in our case was 110 kg./sq. mm. One of the samples tested was extended until it fractured (the fracture being perfectly fibrous), and the second until necking was observed. In both cases the ultimate strength was in perfect accordance with that demanded.

Since I did not carry out any specific overheating tests—as done by the authors in such a

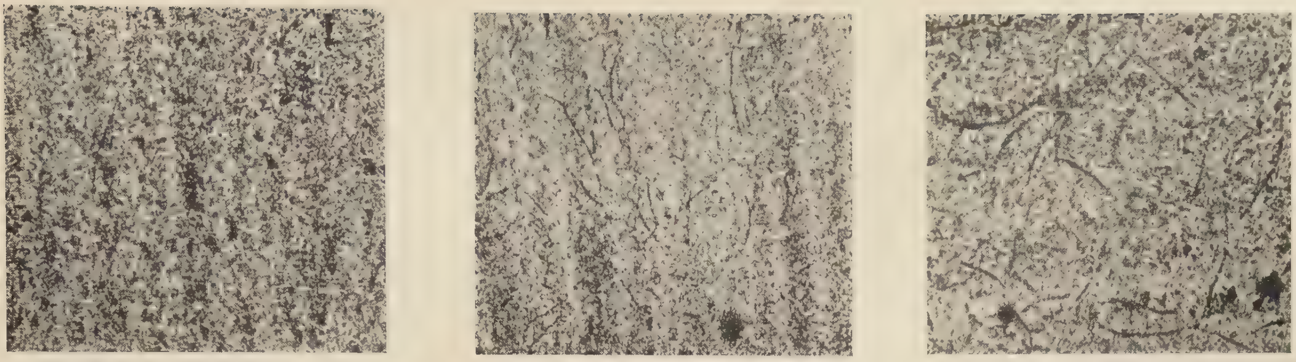


FIG. D(*a*).—Grade *A*. FIG. D(*b*).—Grade *B*. FIG. D(*c*).—Grade *C*.

FIG. D.—Typical Microstructures taken from commencement of fatigue, showing structures overheated to grades *A* to *C*. Etched with nitro-sulphuric acid. × 100. (*See* P. Frith's contribution.)

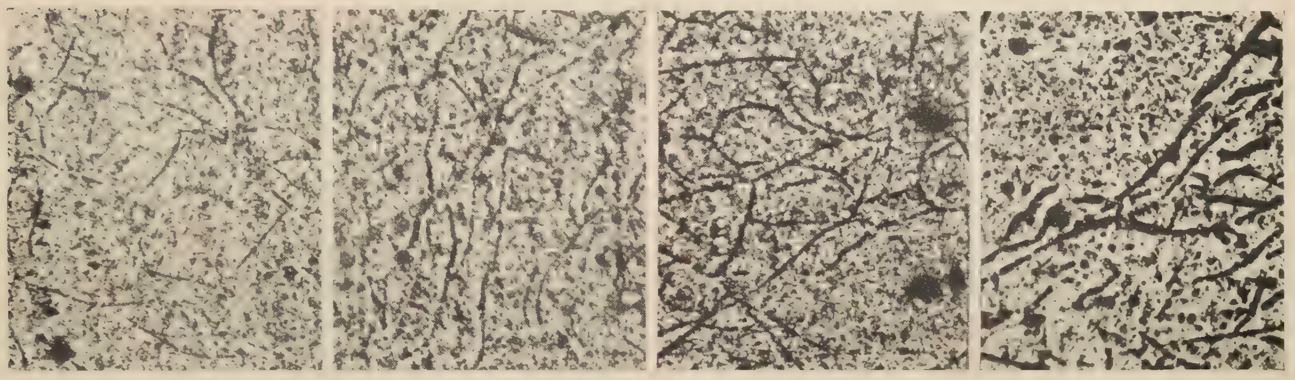


FIG. E(*a*).—Grade *C*. FIG. E(*b*).—Grade *D*. FIG. E(*c*).—Grade *E*. FIG. E(*d*).—Grade *F*.

FIG. E.—Typical Microstructures taken from commencement of fatigue fracture, showing structures overheated to grades *C* to *F*. Etched with nitro-sulphuric acid. × 100. (*See* P. Frith's contribution.)

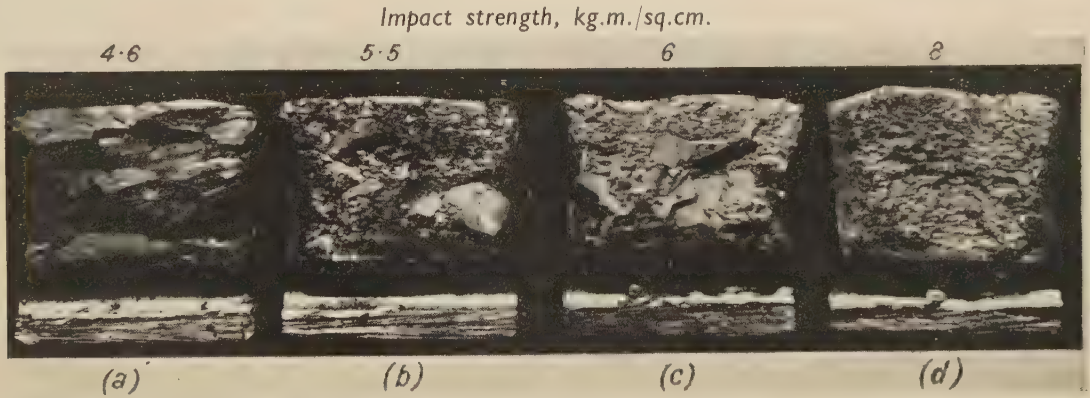


FIG. F.—Fractures of Impact Test-Pieces of acid-electric chromium–nickel–molybdenum steel, ranging from very large facets (*a*) to a fine structure (*d*). (*See* P. G. Bastien's contribution.)

FIG. G.—Etched with 5% alcoholic picric acid. × 450.

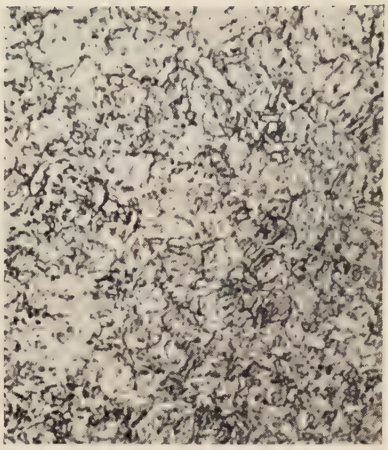


FIG. H.—Etched with 2% nitric acid. × 225.

FIG. I.—Etched with nitro-sulphuric acid reagent (10% sulphuric acid + 10% nitric acid). × 225.

FIGS. G to I.—Micrographs of the sample shown in Fig. F(*a*). (*See* P. G. Bastien's contribution.)

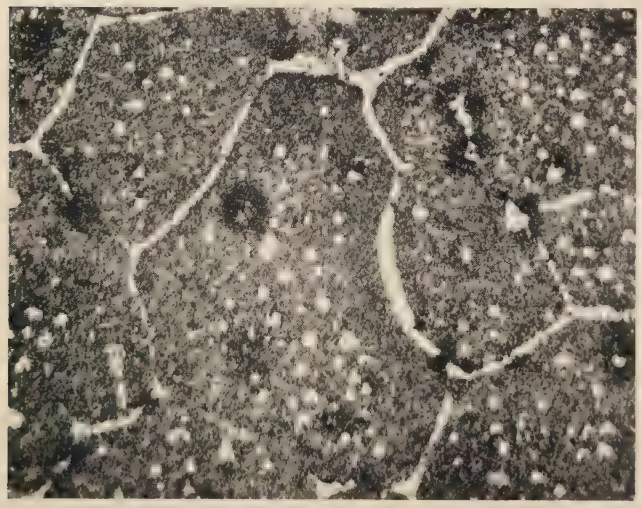


FIG. J.—Sample *A*.

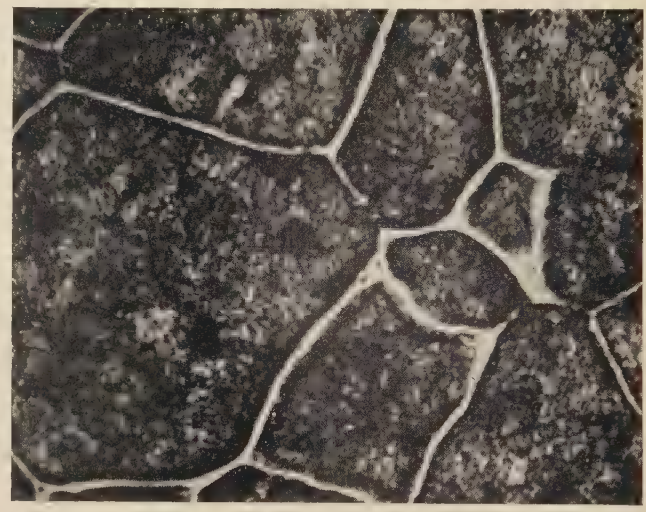


FIG. K.—Sample *B*.

FIGS. J and K.—Microstructures of Overheated Samples, showing the white network revealed when etched with nitro-sulphuric acid reagent. × 500. (*See* A. J. K. Honeyman's contribution.)

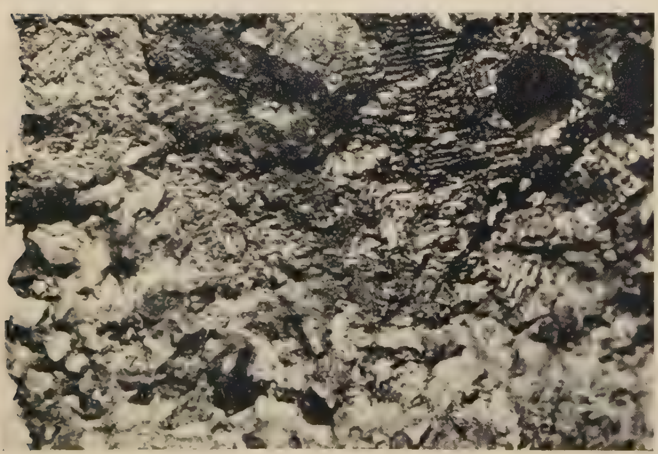


FIG. L.—Fractured Sample taken from the centre of a large, heat-treated $3\frac{1}{2}$% nickel–chromium–molybdenum steel casting, showing coarse, faceted appearance. × 3.

FIG. M.—Fractured Surface of a coarse-grained, laboratory casting after nickel-plating, showing the nature of the fracture to be partly intercrystalline and partly transcrystalline. × 60

(*See* H. Evans' contribution.)

FIG. N.—Drill Rod Sample heated to 2500° F. in air, air-cooled, reheated above Ar_3, quenched, and tempered at 800° F. No indication of overheating. Nital etch. × 100.

FIG. O.—Same Field as in Fig. N, repolished and re-etched in the electrolytic phosphoric-acid etch. Intergranular overheated-grain pattern apparent. × 100.

FIG. P.—*NE* 8735 Steel heated at 2600° F. in air for 5 min., oil-quenched, reheated above Ar_3, quenched, and tempered at 900° F. Electrolytic phosphoric-acid etch. × 100.

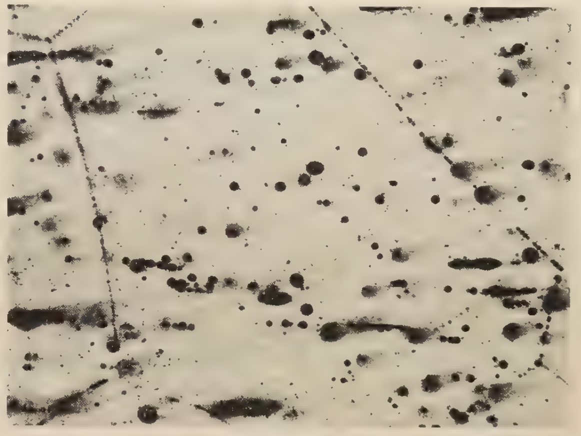


FIG. Q.—Same Sample as in Fig. P, air-cooled from 2600° F.; subsequent heat-treatment the same as for Fig. P. Electrolytic phosphoric-acid etch. × 100.

FIG. R.—Same Sample as in Figs. P and Q, furnace-cooled from 2600° F. Subsequent heat-treatment same as for other two. Electrolytic phosphoric-acid etch. × 100.

FIG. S.—Pressure-Weld Sample deliberately overheated to produce overheated pattern as well as to show weld-plane; reheated in air at 2530° F., air-cooled, reheated above Ar_3, quenched and tempered. Electrolytic phosphoric-acid etch. × 100.

(*See* L. Fine's contribution.)

(Micrographs reduced to three-quarters linear in reproduction.)

Fig. T.—Same Sample as in Fig. S, furnace-cooled from 2530° F. Subsequent treatment and etch same as for Fig. S. Note improvement in weld quality and disappearance of grain-boundary attack. × 100.

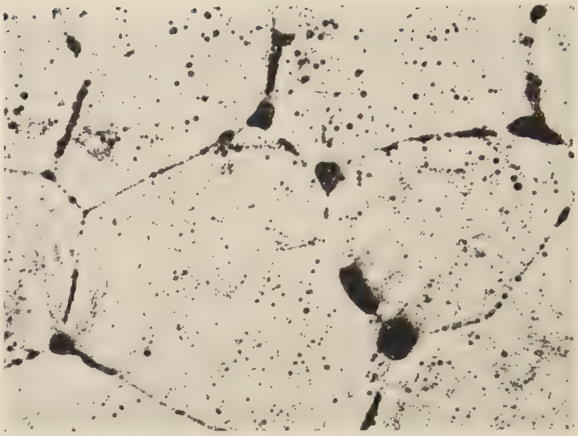


Fig. U.—Medium-Carbon Low-Alloy Steel heated to 2600° F., air-cooled. Appears to be partially overheated and partially burned (presence of large voids). Electrolytic phosphoric-acid etch. × 100.

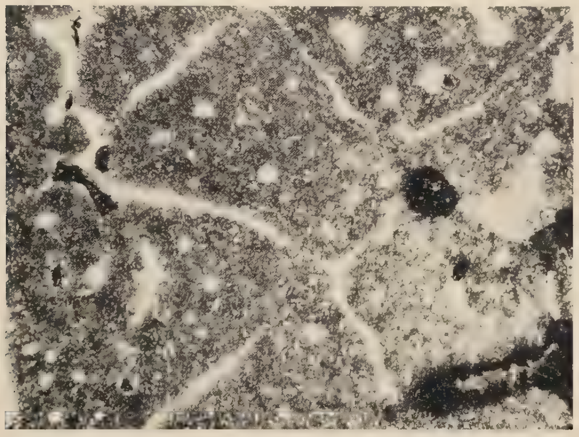


Fig. V.—*NE* 8735 Steel heated in air at 2700° F., air-cooled, reheated above Ar_3, quenched and tempered. Light intergranular pattern. Note general porous condition. Nital etch. × 100.

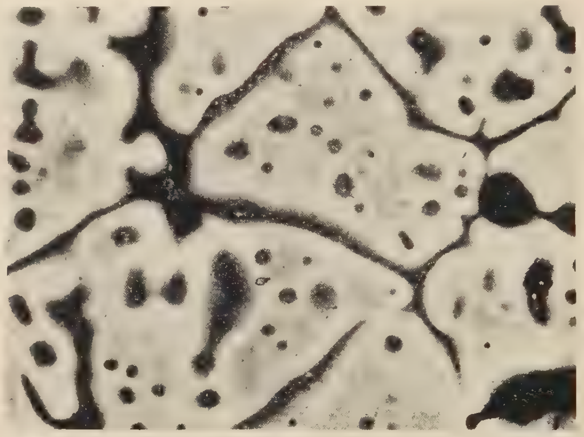


Fig. W.—Same Area as in Fig. V, re-etched in alkaline chromate solution × 100.

Fig. X.—*NE* 8735 Steel heated in hydrogen at 2740° F. As-polished surface shows intergranular pattern of inclusions. Inclusions, checked according to procedure recommended in the American Society for Metals Handbook, appeared to be manganese sulphide. Other portions of specimen showed typical shrink areas and porosity. × 100.

(*See* L. Fine's contribution.)

(Micrographs reduced to three-quarters linear in reproduction.)

comprehensive way—I am not certain whether my opinion that it is essential to avoid a critical degree of forging and heating is quite justified. I should be very much interested to learn the authors' views on this matter. These causes of grain-coarsening would seem to be somewhat out of control, whilst overheating of steel parts can easily be avoided. My opinion on this subject might be summarized in the old rule of the blacksmith: "Do not heat unless you are going to forge adequately."

I am greatly interested in Professor Thompson and Professor Stanton's views on the effect of oxygen on the tendency to burning. I am aware, of course, that it is very difficult to carry out accurate determinations of oxygen in such small regions as those exposed to the flame of an oxy-acetylene torch, but wonder whether the authors succeeded in determining the oxygen contents of their specimens. If so, I should be very much interested in their results, and should like to compare them with those obtained by Rapatz and myself.*

The President (Dr. C. H. Desch, F.R.S.): Not only the papers which we have had to-day, but many research papers which we have had in recent times, have shown the enormous importance of the grain boundary as compared with the general mass of the metal. It is quite obvious that new techniques will be necessary there. Professor Thompson suggested that the solubility of certain of these impurities will be higher in the grain boundary than in the mass of the metal, and I think that is bound to be the case. That will happen if the dissolved impurity lowers the surface tension of the metal. We have very few direct measurements of surface tension of steels, but from experiments on other metals we do know that in general dissolved impurities do lower the surface tension and they become, therefore, concentrated in the grain boundary. Of course, that concentration may not be such as can be detected by ordinary microscopical means, especially when one uses mechanical methods of preparing the surface. The smearing over of the grain boundary—a very fine boundary—masks any defect that might otherwise be observed. With the new technique that has been developed in France recently of electrolytic polishing one should have a better opportunity of using high-power magnification on the grain-boundary material. If one could go a step further and apply the technique of the electron microscope—which, I think, will become much more general—it should be possible to learn something more about boundaries.

There is one thing which has struck me in the few examinations I have made of materials of this kind. There are some of these faceted structures on which there is said to be no sign of melting. That, I think, is partly due to the use of only one method of illumination under the microscope. I remember one specimen in which, when examined under vertical illumination, there would not have been suspected to have been the least melting at the grain boundary but which, when examined under conical illumination, showed clear signs of melting—the flow lines could be seen on the surface, which might easily be overlooked in the course of the ordinary examination.

JOINT CORRESPONDENCE.

(Figs. J to X = Plates XXb. to XXd.)

Mr. R. Whitfield (Incandescent Heat Co., Ltd., Smethwick, Birmingham) wrote: The papers are very worthy of study in spite of the fact that the subject has proved more difficult than anticipated, resulting in the subject being left unsolved; but many leading points are worth following up and whatever the success finally achieved, tribute must be paid to the authors of these papers for their share towards the solution.

Until recently lecturers in iron and steel metallurgy told students about the "burning zone"—that area on the iron–carbon equilibrium diagram embraced by the solidus and liquidus—and that material heated into this area is spoilt beyond repair except by remelting the scrap thus formed. Is this statement still true? It is somewhat difficult to determine correctly the actual temperature at which the forging is used.

It is not easy to see that because the same phenomena was found under vacuum conditions that atmosphere has no influence. A "neutral" atmosphere is still quoted as possible whereas, from the combustion of any fuel, such an atmosphere is impossible. The atmosphere must be oxidizing or reducing, coupled with the possibility of carburizing or decarburizing in either direction. It must be remembered that CO_2 and N_2 are active decarburizing agents in the presence of superheated steam which must be created from the combustion of any normal fuel. What are the

* F. Rapatz, *Zeitschrift für Metallkunde*, 1929, vol. 21, pp. 89–92. F. Rapatz and W. J. Wrażej, *Hutnik*, 1937, vol. 9, No. 1, pp. 5–12.

relations between "burning" and either of the above combinations? In any furnace it is possible to produce desirable conditions so that the scaling and decarburizing are balanced. It is not always realized that decarburization is generally more damaging than scaling, especially at temperatures tending towards overheating and/or burning.

A great difficulty occurs when nascent elements and/or compounds persist in the reactions; these behave very differently from such when they are stabilized. Another difficult factor is that gases under partial-pressure conditions behave differently from those under atmospheric or higher pressures.

However, the important query here is: What is the minimum damage done by keeping clear of the so-called "burning zone?"

Mr. G. Meikle (Ministry of Supply) wrote: These papers are a most useful contribution towards a better understanding of a practical problem which is most annoying when encountered. One of the main difficulties is apparently to decide exactly when a steel is overheated, and it seems obvious that microscopical examination must be the criterion. Even then, there is a degree of uncertainty and different results may be obtained by using different etchants, although the nitro-sulphuric reagent apparently gives the best results. Since there is a strong suggestion that the overheating temperature is connected with oxygen content, it would be of interest to know if Mr. Preece and his collaborators, or any of the other investigators, have tried the alkaline chromate reagent described in a recent paper.* This reagent seems to have a startling effect in revealing areas rich in oxygen and so its use in overheating experiments would probably be most useful.

Mr. Preece and his collaborators rightly point out that the most important property to be considered in an overheated steel is the fatigue strength and, as this is of supreme practical importance, I should like to appeal for early publication of any available information on the effect of overheating on fatigue strength.

Dr. A. L. Norbury (Ministry of Supply, Birmingham) wrote: I have read the paper by Mr. Preece and his colleagues with much interest, and have noticed that the two steels (Nos. 35 and 46) which were exceptions to the general relationship in Fig. 6, would have been "burnt" on account of their high carbon contents (plus a high silicon content in the case of No. 46) at the incipient overheating temperatures recorded. The two exceptions consequently disappear from Fig. 6 and the relationship shown therein becomes more noteworthy.

Mr. G. Burns (Admiralty Engineering Laboratory, West Drayton, Middlesex) wrote: In Table I. of the paper by Mr. Preece and his co-workers there appear to be a few steels in which the overheated structure was not developed, under the conditions of test employed, at any temperature below that at which burning occurred. This would seem to imply that these steels are immune to the phenomenon of overheating; if this implication can be confirmed as being fact the steels in question become of considerable importance in demonstrating that steels can be made which are, firstly, immune to overheating and, secondly, presumably devoid, or nearly devoid, of the constituent or constituents that produce the characteristic overheated structure by their diffusion during cooling from the overheating temperature.

However, before these steels are accepted as being immune to overheating, it would seem necessary to examine them more fully to confirm that they will not under any circumstances develop an overheated structure. For instance, it would be advisable to check that they will not develop the overheated structure if cooled through the appropriate temperature range at rates other than that used by the authors in the main part of their work. There is an apparent discrepancy between the findings of Mr. Preece and his co-workers, on the one hand, and those of Messrs. Woolman and Kirkby, on the other, as to the cooling rates at which the overheated structure can be developed, and it would seem that further examination of this point might be worth while. Further, the writer has observed a dark-etching network developed by the nitro-sulphuric reagent in steels flash-welded in small sections which, owing to conduction to the water-cooled clamps, had cooled from the welding temperature at a rate fast enough to cause hardening not much less than would have been developed by oil-quenching; this observation would suggest that in some circumstances an overheated structure can be developed during cooling at a much faster rate than that used by the authors.

Unless a range of constituents is involved in the susceptibility of steels to overheating it is difficult to see why the minimum temperature required to develop the phenomenon should vary so widely, even among steels of closely similar composition, and it may be pertinent to enquire whether this variation is in fact as wide as it appears, or whether the variation found in this work is in part due to the use of an approximately constant cooling rate for all the steels. The use of gradient cooling, covering as wide a range of cooling rates as possible in one bar, would seem a suitable method of attack on this question.

In view of the fact that cooling rate through

* L. Fine, *Metal Progress*, 1946, vol. 49, No. 1, p. 108.

the overheating range is a factor in determining whether the characteristic structure and behaviour are developed or not, it may be worth while recalling that Dr. Whiteley, in his work on austenite grain growth, found that the cooling rate through approximately the same temperature range had a marked effect on the grain-growth characteristics of a steel during subsequent heating. Comparison of the grain-growth characteristics of a sample of steel in which the overheated structure has been developed with those of a sample heated to the same temperature but so cooled that the overheated structure is not developed, might provide some useful information.

The statement that the authors are continuing the investigation is welcome, for at the present stage of the work the phenomenon, though more clearly defined, seems to have become more elusive than ever.

Mr. H. W. Kirkby (The Brown-Firth Research Laboratories, Sheffield) wrote: I would like Professor Thompson and Dr. Stanton to consider whether there might be another explanation for the displacement of the S curve than the one put forward in their paper. In effect, they consider that dissolved oxygen has reduced the hardenability (displacement of the S curve to the left), the dissolved oxygen being introduced by the localized burning. Heating a piece of steel to near fusion temperatures is, however, a complex affair and not nearly as simple as the paper would have one believe. In this respect, I would refer to a paper by Whiteley * which, among other things, dealt with the grain-growth characteristics of a 0·45% carbon steel as affected by the rate of cooling from high temperatures. He showed that a steel having an inherently coarse-grain character could be modified by heat-treatment such that the same steel acquired inherently fine-grain characteristics.

Briefly, Whiteley showed that by heating to a temperature of 1250° C. and above, and cooling at a fairly fast rate (air-cooling) the material (which had inherently coarse-grained properties) when reheated subsequently to 930° C. showed fine-grain characteristics. Increase in the initial heating temperature above 1250° C. resulted in a progressive retardation of grain growth when reheated at 930° C. He also found that this retardation effect was a function of the cooling rate from the initial high temperature:

Conditions of heating: 15 min. at 1390° C. and 30 min. at 930° C.

Rate of Cooling.	Grain-Size Characteristics.
Fast . . .	Fine (1500 grains in 10 sq. in. at 100 magnifications).
Slow . . .	Coarse (19 grains in 10 sq. in. at 100 magnifications).

The writer tried this out in an acid open-hearth cast of 0·40% carbon steel some time ago by heating two samples to 1375° C. for ½ hr., furnace-cooling one to 1100° C., then air-cooling and water-quenching the other. Both samples were then heated to 930° C. for ½ hr. and air-cooled. Subsequent micro-examination confirmed Whiteley's work in that the slowly cooled specimen was coarse-grained, whilst the water-quenched sample appeared to have a very fine grain, although whether the effect produced in the water-quenched sample was the true grain-size is a matter which has still to be determined. Nevertheless, the samples in question did indicate that the austenitic-breakdown characteristics of the steel in the two conditions differed widely. A further and very important point was that neither sample showed any evidence of oxide boundary films.

The point which all this is leading to is that with such a difference in grain-size (or, alternatively, the breakdown characteristics) differences in hardenability might be expected, the finer-grained material giving the lower hardenability. Relating this to the authors' work, it can be seen that similar conditions may quite well exist. Thus, the 0·82% carbon steel may be a steel having inherently coarse-grain characteristics. The portion heated to a high temperature and quickly cooled would result in the locally heated material being modified such that on reheating it had a fine-grain habit and hence a lower hardenability.

The writer submits that the above may constitute an explanation of the differential hardenability effect noted by the authors and that it is not due to oxygen introduced in the burning operation. It may also explain why the authors' experience with the steels tested by them is varied, since the effect observed by Whiteley does not, of course, occur in steels which are made inherently fine-grained. In other words, the steels which respond to the authors' treatments are inherently coarse-grained, whereas the steels which are not affected by local burning are of the inherently fine-grained type.

The explanation of the displacement of the S curve vertically appears to have little supporting evidence.

The paper by Mr. Preece and his collaborators has many points of similarity with the paper by Mr. Woolman and myself and, in general, the agreement is good. There are a few points, however, which require comment.

The authors found that the clearness of the structure obtained by the nitro-sulphuric reagent was independent of the condition of heat-treatment. My own experience is that the clearness referred to is liable to wide variations, some

* J. H. Whiteley, *Journal of The Iron and Steel Institute*, 1943, No. II., p. 513 P.

samples having a prominent cellular structure, whilst others could only be described as having a faint pattern. This may be wrapped up in the initial conditions of overheating, particularly in regard to the rate of cooling, and work is in hand covering this aspect of the matter. At the moment, it would appear that the intensity of pattern is at, or near, its maximum when the rate of cooling from the overheating temperature approximates to air-cooling a 1-in. square or 1-in. dia. bar. This, of course, is the rate of cooling adopted by the authors and probably accounts for the results obtained.

A further matter is in connection with the effect of overheating temperature on the Izod value. It would be of interest to know whether the results were modified in any way by including in the final treatment a normalizing treatment at, say, 50–100° C. above the normal hardening temperature before oil-hardening and tempering. This is suggested on the grounds that after a high-temperature treatment satisfactory refinement is not always accomplished with one heating into the austenitic region (in this case, heating for hardening) and a prior normalizing treatment is a great help in this direction. Thus the Izod tests would then be carried out on a reasonably refined structure as distinct from a rather doubtfully refined one. In other words, the use of a normalizing treatment would separate two factors : (*a*) The influence of overheating in terms of a facet fracture, and (*b*) the influence of overheating in terms of a poorly refined structure. The argument in regard to grain-size is illustrated by the following :

Type of steel : 3% Nickel–chromium–molybdenum.
Condition : Overheated in forging, giving very large grain-size but no facets. Annealed by slow-cooling from 850° C.

Micro-Examination.

In spite of the annealing treatment a coarse grain pattern was still evident, although the grain-size appeared much finer.

Results on further reheating on a laboratory scale were as follows :

(i) After ½ hr. at 850° C., A.C., T. 600° C.	Coarse grains still evident as a ghost-pattern, together with new and much finer grains.
(ii) After a second treatment as (i).	Coarse grain pattern still evident, but much fainter.
(iii) After a third treatment as (i).	Coarse grain pattern almost disappeared.

Another sample was treated as follows :

(iv) Normalized at 950° C., ½ hr. at 850° C., A.C., T. 600° C.	No coarse grain pattern visible.

Mr. Merchant's paper makes it clear that the term "overheating" requires clarification in order to avoid confusion of thought. Thus, whilst the author states that a faceted fracture is indicative of overheating, the issue is confused by reference to large crystal size as revealed by the normal etching reagents (*i.e.*, nital, picral, &c.). Whilst facets are generally associated *at some stage* with a large grain-size, a large grain-size as revealed by these etchants does not necessarily mean that such a steel will give a faceted fracture. Thus the final grain-size (*i.e.*, the grain-size which has been produced by, say, the final hardening) may be very fine and the fracture may show facets. On the other hand, a grain-size may be classified as coarse and show no facets.

There are at least two definitions of overheating :

(1) A coarse grain structure revealed by etching with, say, 2% nital or saturated picral. This grain-size can be refined in most cases by heat-treatment.

(2) A faceted fracture produced after final hardening and tempering. This is generally coupled with the cellular pattern (produced by the H_2SO_4–HNO_3 reagent) which is thought to represent the austenite grain-size existing at the overheating temperature. The actual grain-size is very often much smaller as a result of further heat-treatment.

With regard to the phenomenon of "crozzling," the writer is of the opinion that this is not necessarily a guide to overheating in terms of a faceted fracture, although, in many cases, it does give an approximate measure of the grain-size existing at the initial heating temperature.

Finally, in any classification of degrees of overheating by the use of standard fractures, the rate of cooling from the overheating temperature should be considered.

Dr. L. Colombier (Établissements Jacob Holtzer, Forges et Aciéries d'Unieux, Loire, France) wrote : I have read with great interest the various papers on the overheating of steel, and was very pleased to find complete confirmation of the observations which I myself had published in 1942.* For reasons which will be easily understood, this publication presented practical conclusions in a somewhat summary form, and was not widely distributed.

From all these papers, certain definite conclusions can now be drawn :

(1) There is a minimum heating temperature above which facets appear in the fracture of the steel treated. This minimum temperature varies with different steels; it is a matter of a specific property of the metal, independent

* *Bulletin du Cercle d'Études des Métaux* (*St. Etienne*), 1942, vol. 3, pp. 146–158, 265–268.

of the external conditions, particularly the method of heating. On the other hand, the conditions during steelmaking and especially deoxidation play an important part.

(2) The dimensions of the facets increase as the temperature of heating rises; there is a relationship between the grain-size of the fracture and that of the austenite at the temperature considered.

(3) Even strong overheating, provided that it does not reach the burning temperature, with melting of the segregated elements, can easily disappear during further forging. If it is not too strong, it can be suppressed by the usual treatment of regeneration. It must further be remarked in this connection that when overheating has apparently disappeared, the steel giving a perfectly sound fracture after normal treatment, it can reappear if the steel is rendered brittle by tempering in the critical range.*

(4) Overheating affects the mechanical properties of the metal; the resilience (resistance to impact of a notched bar) is particularly diminished, as has been shown by J. Vernay † and by myself (*loc. cit.*). The fatigue limit, on the contrary, varies relatively little in Vernay's experimental conditions (*loc. cit.*). Mr. Merchant's results are also rather inconclusive, because after overheating at 1300° C. this characteristic is not sensibly altered.

The theoretical interpretation of all these facts is not easy. I have proposed the following :

It must be remarked in the first place that intergranular fracture is the normal mode of breaking of all steel quenched after heating to a temperature sufficiently high for notable grain growth to have occurred. It can be seen starting from a grain-size of about No. 5 on the Jernkontor scale. It is, for example, the fracture of a 1% carbon steel after quenching from 950° C. If the steel so quenched is tempered at increasing temperatures, it is observed that the intergranular fracture disappears at a temperature which rises as the degree of overheating increases. In the case referred to above, it disappears at about 400–450° C. after quenching from 950° C. and at about 550° C. after quenching from 1100° C.

Overheating is thus defined in a somewhat arbitrary manner by the persistence of intergranular facets in steel quenched and tempered at 600° C.; the definition would be different if one chose a different tempering temperature—500° C., for example.

The conclusion to be drawn from these observations is that in reality there is no discontinuity in the phenomena of overheating; one can speak of a limiting temperature only in reference to particular experimental conditions.

When a steel is heated in the austenitic range a certain equilibrium is established between the grains; their sizes depend on the temperature and on the time during which the temperature is maintained. What is the true nature of the boundaries between these grains? That is a question to which a reply must be found if we wish to understand the phenomena of overheating. Since quenched steel fractures along these boundaries rather than through the grains, the boundaries must persist in the martensitic state, which gives them greater brittleness and less cohesion than of the grains themselves.

The relative cohesions of the boundaries and of the grains can be reversed by tempering at a sufficiently high temperature, but even then the material substance of the boundaries is not destroyed, because, in metals sensitive to temper-brittleness, a second tempering at a lower temperature can cause the intergranular fracture to reappear.

Except in the case of overheating at the highest temperatures, micrographic examination of the quenched or quenched and tempered metal, with or without intergranular fracture, reveals nothing of these boundaries. It is only when the grain has grown considerably (and with it the thickness of the boundary) that the nitro-sulphuric etching reagent shows up a difference of susceptibility to chemical attack between the body of the grains and their frontiers. But there is nothing to justify the assumption that these boundaries are marked by the presence of a constituent insoluble in austenite, in martensite, or in the sorbites. Further, the hypothesis that non-metallic constituents accumulate in these boundaries has long been refuted, and I think that equally the hypothesis of a precipitation such as is imagined by Mr. Woolman and Mr. Kirkby must also be rejected.

It is, in fact, contradicted by observations that I have been able to make recently during researches (as yet unpublished) on the rôle of phosphorus and of silicon in the phenomena of overheating, and of which the conclusions are summarized in the following. These tests were carried out on a self-quenching nickel–chromium–molybdenum steel made in a high-frequency furnace. Three melts with various silicon contents were prepared, and to these, after pouring off part of the metal, ferro-phosphorus was added. Sensitivity to overheating was judged by the persistence of intergranular facets after various treatments, among which only the following will be quoted here : 1275° C. for 2 hr. (air) + 900° C.

* Colombier, *Bulletin du Cercle d'Études des Métaux* (*St. Etienne*), 1945, vol. 4, pp. 229–232.

† Vernay, *Bulletin du Cercle d'Études des Métaux* (*St. Etienne*), 1942, vol. 3, pp. 159–169.

(air) + 650° C. (air) + 875° C. (oil) + 600° C. (oil)—that is to say, overheating followed by a treatment of regeneration and then the normal final treatment. The following results were obtained :

Silicon Content.	Phosphorus Content. 0·020%	0·040%
0·28%	No overheating.	Traces of overheating.
0·36%	Very feeble traces of overheating.	Strong overheating (50% intergranular).
0·50%	Clear traces of overheating.	Very strong overheating (two-thirds intergranular).

The influence of phosphorus and silicon is thus very clear. Further, these two elements and their compounds, phosphide or silicide, are equally soluble in austenite and in martensite, and one cannot imagine the precipitation of these elements in the grain boundaries.

We are thus driven to admit that heterogeneity of concentration exists in the solid solution itself. On the basis of ideas put forward by Benedicks * one can represent them in the following manner : He explains the tendency to grain growth by the existence, at the surface of contact between two grains, of a surface tension analogous to that existing at the contact suface between two liquids or between a liquid and a solid. As a consequence of the existence of such a surface tension the concentration of the elements dissolved in the austenite is not uniform. It will be remembered that in liquid solutions the surfaces of separation from the air or from the container have been observed to be enriched in dissolved bodies when the latter diminish the surface tension. It is not unreasonable to suppose that analogous phenomena occur in solid solutions and that there is an enrichment in certain elements towards these surfaces of contact which constitute the grain boundaries. By this mechanism the concentration of elements such as silicon and phosphorus would be greater towards the grain boundaries, constituting in the body of the austenite a heterogeneous network which would persist in the metal after it had become martensitic, and would thus explain the heredity observed through successive transformations without the necessity for these elements to be precipitated out of solution.

The influence of these heterogenities (that is to say, the local concentration of the elements considered) increases as the grain-size itself increases, which no doubt can be explained by the smaller total superficial area of the boundaries. In the theory of surface tension, this point is not quite clear; account should perhaps be taken of the variations of these tensions (or of the influence of elements on them) with temperature. As measurement is quite impossible, we are reduced to hypotheses. However that may be, everything takes place as if the influence of the boundary increased as the grain itself increased. Starting from a certain size, varying, of course, with the nature of the active elements, the brittleness of the boundary becomes such that rupture takes place preferentially between the grains—that is, intergranular fracture.

If a steel presenting such a phenomenon is heated a little above the Ac_3 point, the new austenite will be fine-grained, a new equilibrium will be established, and the elements dissolved in the austenite will distribute themselves along the new boundaries, with less enrichment. The steel will no longer be sensitive to intergranular fracture—it will have been regenerated. If, nevertheless, particularly large concentrations pre-existed, the rate of diffusion might be insufficient, at lower temperatures in the austenitic range, to assure an entirely new redistribution of the elements; signs of overheating could persist. Several treatments carried out at higher temperatures might be necessary to regenerate the metal. Finally, in the case of extreme overheating, or when the solubility of the intervening element was low, the enrichment of the boundary might be such that the limit of solubility was exceeded; then precipitation would occur, corresponding to the case where the boundary could be revealed by micrography.

Thus, overheating may be considered as a superposition of two phenomena :

(1) Grain growth as the temperature rises.

(2) Enrichment of the austenitic solid solution in certain elements towards the grain boundaries.

It is by their action on the first phenomenon that we explain the fact that steels rich in inclusions are less sensitive to overheating. The inclusions are also obstacles to grain growth; they behave, for instance, like the carbide in a carbide-containing steel. It is known that a very fine distribution of carbide constitutes a very effective hindrance to grain growth: the influence of inclusions and the favourable effect of a high content of oxygen on the sensitivity to overheating are thus easily explained.

It is, on the contrary, by their action on the second phenomenon that we explain the part played by phosphorus and by silicon.

With regard to aluminium, of which the effect is not in doubt, it can influence the grain growth by slowing it down by the fine precipitation of alumina to which it gives rise in the steel; but the excess of aluminium itself in the metal should undergo the same phenomenon of enrichment in the boundaries. In fact, I have shown in the researches quoted above that after the addition

* Conference at the Seventeenth Congrès de Chimie Industrielle, Nancy, 1938.

of 0·010% of aluminium intergranular fracture took place after overheating at a temperature definitely less than that before its addition, even though the grain growth was also much less. That is a striking example of the simultaneous action, and in reversed directions, of an element on the two parts of the phenomenon of overheating. Here the action on the second part is of much greater importance, to the extent that the presence of aluminium obstructs the regeneration of the metal.

I hope that these few reflections may help to clear up some points still obscure; no doubt considerable research is still necessary before we shall have a complete knowledge of these phenomena, but from now onwards a clear representation of many of the observations is possible. I shall be very happy if progress can result from the collaboration of metallurgists, so long separated, on the two sides of the English Channel.

Mr. A. Hartley (Leeds University) wrote: There seems to be some doubt about the values of the various etchants recommended for overheated steel. A study of many reagents, applied to steel in all stages of overheating, suggested that only two, nitro-sulphuric acids and electrolytic ammonium nitrate, will detect overheating in its incipient stages. Mr. Goodrich finds the latter unsatisfactory, but Figs. 17 and 18 of our paper show the typical structure developed by this reagent on a steel of the same composition as that used by Mr. Goodrich.

The application of the 2½% nitric acid reagent to many types of steel has shown that it is not of general use as a means of detecting slight overheating. We found that this etchant gave broad white boundaries and white pools in the interior of the crystals of severely overheated steel in the air-cooled condition. To obtain this structure, however, the steel generally had to be heated above 1400° C. The boundaries and pools appeared to etch black in tempered specimens. There was some evidence that this type of boundary was the same as that which was etched black by ammonium nitrate (Fig. 16 of our paper). With this latter etchant, however, there was no inversion of the boundary effect on tempering.

Mr. Merchant refers on p. 228 P to the necessity of using special etching reagents to detect burning, but is not this phenomenon shown by oxide films and voids in the unetched specimen?

On p. 219 P Mr. Merchant suggests that overheating cannot be caused by a transient increase in temperature on forging. It has been stated, however, that overheating may occur when a steel is heated rapidly by induction methods and hence the momentary rise in temperature on forging may be quite sufficient to cause the development of this condition.

An interesting point emerges from the measurement of the overheating temperatures of the carbon–chromium steels (En 31). Recently published diagrams * indicate that the solidus of this steel is in the region of 1250° C., but we have shown that certain casts of this steel can be heated to 1275° C. without being overheated and this is confirmed by Mr. Woolman and Mr. Kirkby. It is impossible to exceed the solidus by almost 50° C. without the steel showing signs of overheating or burning and this would suggest that the solidus as given is incorrect.

Mr. F. E. Stokeld (The Deritend Stamping Co., Ltd., Birmingham) wrote: I have read the present series of papers and listened to the discussion thereon with much pleasure. Mr. Merchant's paper dealt with the matter from the drop-forgers' point of view more than did the others, but upon considering some of the remarks that were made during the discussion, I feel that there is another aspect of the case which merits some attention.

The overheating of steel at drop-forgers' works has been an occasional trouble for many years, but it should be noted that the amount thereof was usually very small. The disadvantages of poor heating equipment in the past were largely offset by the skill of the heater employed at the hammer, but several additional disadvantages have had to be dealt with by drop-forgers during the war.

In the first place, poor fuels had to be used; *e.g.*, low-quality coal for pulverizing and also creosote–pitch mixture, instead of the more usable fuel oil, and there was insufficient town's gas to make up for deficiencies in other directions. To make matters worse, a lot of untrained labour had to be employed in order to meet the demands for the vastly increased quantities of drop-forgings required during the war. Furthermore, there appeared to be a general increase in the stress to be withstood by forgings of earlier design, *e.g.*, owing to the additional horse-power of aero-engines and of load-carrying requirements. It now appears that since steels for the aircraft industry are the cleaner steels they would be the more readily susceptible to overheating.

The general effect of such factors as these eventually culminated in the serious wartime outbreak of overheating and, in 1943, this led to the formation of a Committee sponsored by the Ministry of Aircraft Production to deal with the matter. This was the Joint Advisory Committee on the Overheating of Steel Drop-Forgings, under the Chairmanship of Mr. H. H. Burton of the English Steel Corporation, Ltd. This Committee was composed of metallurgists from steelmakers, drop-

* W. Tofaute and others, *Archiv für das Eisenhüttenwesen*, 1936, vol. 9, p. 606.

forgers, the aircraft industry, and from the A.I.D. Materials Branch, together with the Director of Drop-Forgings. In that year the Committee issued an Advisory Publication to all drop-forgers. This document declared that the responsibility of preventing overheating rested with the drop-forgers and advised them of the state of knowledge on the subject and how the matter could best be dealt with. It laid down a method whereby those firms who had been unsuccessful in solving their own difficulties could call upon the services of the Committee, who would arrange for technical men to visit their works and advise them of the best way out of their trouble. It also required that every case of overheating, whether solved or not, should be reported to the Director of Drop-Forgings for consideration by the Committee. It is noteworthy that the number of cases reported became fewer as the work of the Committee proceeded.

Most of the information published in the present series of papers was known to the Joint Committee in 1943, except, perhaps, that the means of refining overheated forgings by cooling slowly from high temperatures, as shown in the paper by Preece and his co-workers, and also that the recent advances towards a better understanding of the nature of overheating, were not then available. It was thoroughly understood, however, that the only rational way to deal with overheating was to prevent it and this became still more evident in the course of time.

In 1944 an open discussion on the subject was held by the Midland Metallurgical Societies in Birmingham. References were made to the work being carried on at Leeds University and elsewhere, but no distinct advances in the treatment of the subject were then apparent. We were greatly indebted to the Bristol Aeroplane Co., Ltd., however, for their further information on the effect of the various grades of overheating upon the fatigue values of the 100-ton/sq. in. nickel–chromium steel: this was upon the lines of Mr. Frith's useful contribution to the discussion on the present papers. One point remains to be cleared up: Whilst we have been told that slow cooling from high temperatures is effective in restoring the mechanical properties of overheated steel, we have yet to learn whether this also applies to the reduced fatigue values. It is hoped that some work now in hand at Birmingham University may be helpful in this connection.

Even from the present series of papers it is evident that non-destructive methods for the detection of overheating are still inadequate. All practicable methods that have come to our notice have been tried out at the works and laboratories of my employers, The Deritend Stamping Co., Ltd. We have installed a plant for the pickling of forgings in boiling hydrochloric acid on a production basis for suspected cases of overheating and have found this method of great service to ourselves and others. We can confirm, however, that when forgings have been machined, or have been thoroughly descaled by shot-blasting, they are rendered unsuitable for judging as to whether they have been overheated or not, although evidence of burning can be made clearer by this means.

Despite the fact that we can claim to have had a fair measure of success in refining by heat-treating forgings that showed slight signs of overheating, all our experience has supported the early opinion that the only proper way to deal with overheating was to prevent it.

Under the present circumstances, it appears to me that the application of precise knowledge is essential in order to prevent overheating. The first thing is to decide upon a maximum temperature which that of the steel about to be forged must not exceed. The next thing is to provide the forge with furnaces that will economically heat the steel to no higher than this temperature, even when the steel may be kept in the furnace owing to delay at the hammer, &c., for longer periods than usual.

The Joint Advisory Committee did not consider it desirable in 1943 to lay down fixed maximum temperatures for the heating of steels for forging in all plants since the conditions differed so greatly; but the publication issued to drop-forgers advised them that every effort should be made not to exceed 1250° C. for the majority of alloy steels used in the aircraft industry. In practice, this was found to be fairly successful. Nevertheless, cases of overheating of some electric steels were observed when this temperature was not exceeded. On the other hand, I have seen no true evidence of an open-hearth steel being overheated when 1200° C. was not exceeded; nor of an electric steel when taken to no higher than 1150° C.

Clark,* in a paper which is useful at this point, shows that of about 70 different steels which he investigated, excluding the graphitic steels and one tool steel, the safe maximum temperature may be as low as 1150° C., or as high as 1320° C., according to the particular steel involved. Unfortunately, the method of steel manufacture is not stated, but it is interesting to observe that several pairs of steels of almost exactly similar composition show variations of about 60° C. from one to another. Indeed, he shows a difference of 140° C. (1290–1150° C.) in the recommended maximum forging temperatures of one pair of 5% chromium–molybdenum steels. These were very similar except that one contained 0·44% of titanium.

* C. L. Clark, *Iron Age*, 1944, vol. 153, Mar. 16, pp. 52–55.

Based on the above and upon other evidence, something like a working proposition begins to emerge. In general terms, it might be stated thus: Electric steels should be heated to no higher than 1150° C. and open-hearth steels to no higher than 1200° C. for forging. Many forging operations can be completed from these temperatures, but when economical production appears to require a higher temperature it becomes necessary to find by experiment the maximum permitted forging temperature of the particular cast of steel involved. Making due allowance for the amount of hot work to be performed and the approximate finishing temperature of the forging operation itself, the safety controls can then be fixed and manufacture can proceed safely.

It is clear that overheating can be prevented by this means and it is found that the main problem in actual practice is a matter of furnace design, *viz.*, to ensure correct control of the temperature to which the steel is heated prior to forging.

In a paper* published in the *Drop Forger*—the official journal of the National Association of Drop Forgers and Stampers—I have attempted to bring to the attention of drop-forgers some idea of the lines upon which this problem might be tackled. This paper did not deal with the comparatively simple matter of heating numerous pieces of regular size and shape for regular forging operations and therefore made but small reference to those methods employing electrical-resistance or high-frequency heating. Instead, the matter was confined to the problem of heating in fuel-fired furnaces, each of which must be capable of dealing with a variety of different sizes, shapes, and classes of steel bars or billets and also with partly made, or nearly finished, forgings.

The preceding sentence indicates the real problem that drop-forgers have to face; for there is seldom a sufficient regularity of production of similar forgings required over a long enough period to permit the installation of specialized heating equipment which, whilst it may be ideal for one or two patterns of forging, would be quite useless for many others to be made at the same hammer. A quite different state of affairs exists in many plants in the United States of America where long runs are the rule rather than the exception. Indeed, I have seen it stated that the production at one plant would not be changed until at least 500 tons of steel were available "at the hammer" for one new pattern of forging about to be produced. Nevertheless, we have seen that overheated forgings can be produced even in the U.S.A., but it is hoped that the work of Jominy, Strauss, and others may be instrumental in reducing such undesirable exports in future.

Without the undoubted advantages of very regular production, British drop-forgers have to employ heating equipment that is very versatile in respect of the sizes and shapes of the pieces it will accommodate. Many so called "furnaces" in the past were no more than smoke-belching "flame boxes" in which the steel was heated and where the man at the hammer exercised the only "control" possible under such conditions. Heating for forging was thus a highly skilled occupation, albeit an uncomfortably hot and dirty one.

A great deal of valuable work has been accomplished since then and at my employer's works a new conception has arisen. On one of our newly developed furnaces, fired by town's gas, where there is no actual flame in the working space and the temperature is automatically controlled to within $\pm$ 7° C., the man at the hammer told me that his only complaint was that he had to have his coat on to keep warm! This development marks a stage in real progress towards the better heating of steel for forging so that, not only can precise temperature control be established in the forge as a major factor in the prevention of overheating, but a far cleaner stamp shop is envisaged, with better working conditions for the man at the hammer. It is thought that such an improvement would tend to attract a better class of workman, who would be more likely to lend brains rather than only brawn to the manufacture of the highest quality of drop-forgings yet produced.

It will be apparent from the foregoing remarks that, despite the impression that may have been gained from the contribution of Mr. Latta to the discussion, some drop-forgers, if not all, have been taking the necessary steps to deal with the matter of preventing overheating and the work is still going on. Indeed, some have proceeded so far along the road to success that, for instance, my own employers have been able to guarantee freedom from overheating quite confidently upon accepting a recent order for making certain highly stressed forgings and it has since transpired that the confidence was not misplaced.

In conclusion, I would like to record my personal thanks in appreciation of all the good work already accomplished that rendered possible the present series of valuable papers and the numerous useful contributions to the discussion. It is hoped that the authors of the papers may be thus encouraged to continue the good work so that eventually the steelmakers may be able to produce steels of such regular characteristics that none of them will be susceptible to overheating below a fixed temperature of, say, 1250° C. which surely should be adequate for the drop-forging industry.

Dr. V. Kondic and Dr. J. A. Wheeler (Metallurgy Department, The University, Birmingham)

* F. E. Stokeld, *Drop Forger*, 1945, vol. 25, No. 1, p. 11.

wrote: Attempts to define the term "overheating" have so far been of two kinds, one group being based on the effects of heating to high temperatures on various mechanical properties, and a second group, to which the definition proposed by Woolman and Kirkby belongs, on the corresponding effects on structural characteristics, such as the appearance of network structures or faceted fractures. As the practical implications of the use of the term always relate to the mechanical characteristics of the material to which it is applied, we believe that definitions of the first type offer more prospect of receiving general practical acceptance. However, it is not yet clear which of the mechanical properties should be selected to form the basis of such a working definition, nor in what condition of heat-treatment the material should be tested. The fracture method of determining minimum overheating temperatures which has been adopted by Preece and his co-workers gives good correlation with the results of static mechanical tests for certain steels, as is indicated by Figs. 7 and 8 of their paper, but this principle may not hold for all steels. For example, no such relation exists for certain nickel–chromium–molybdenum steels which we have tested in the air-hardened condition. A steel containing 0·35% of carbon, 3·4% of nickel, 1·7% of chromium, and 0·47% of molybdenum, first showed faceting of the tensile fracture after heating at 1130° C.; there was no evidence of the network structures which constitute the other proposed test for overheating and, furthermore, the ductility properties actually attained maximum values in this temperature range. On the other hand, a similar steel containing 0·24% of carbon, 4·18% of nickel, 1·30% of chromium, and 0·68% of molybdenum, showed no faceting of the tensile fracture after heating to 1370° C. in spite of the fact that this had caused a 40% decrease in both elongation and reduction of area.

On the basis of evidence of this kind we hold the view that while overheating—in the sense of impaired mechanical properties—and the development of faceted fractures, frequently occur as parallel phenomena on raising the temperature of heat-treatment, it does not therefore follow that there is a direct connection between them, or that the fracture test can give more than a very general guide on questions of mechanical soundness.

We have studied several steels very similar in composition to that used by Goodrich, and find that relatively minor differences in composition may be associated with widely dissimilar fracturing characteristics after the same heat-treatment. For this reason we should welcome the extension of his work to other steels in order to investigate the generality of the conclusion which he draws.

Our experiments on the restoration of the mechanical properties of badly overheated steel have led us to the conclusion that the most complete solution consists in repeated heat-treatment at continuously decreasing temperatures—a procedure similar to the American method referred to by Merchant. By this means, and by using highly protective inert atmospheres for all heat-treatments, we have found it possible to reproduce the static mechanical properties characteristic of a heat-treatment temperature of 900° C. in a specimen which had previously been heated to 1400° C. On the very important question of the fatigue properties of specimens so reclaimed, we have, however, no evidence.

Mr. W. Walker (The Clyde Alloy Steel Co., Ltd., Motherwell) wrote: The publication of these papers on overheating clears up many points which have long been the cause of much discussion and controversy between steel producers and forgers. It has always seemed rather surprising that so little was known about the exact nature of this phenomenon, particularly when one considers the number of forgings which have been rejected at various times because of this defect.

About a year ago, as a result of one of the frequent discussions which arose concerning overheating, the writer undertook, in the research laboratory of The Clyde Alloy Steel Co., Ltd., a fairly comprehensive investigation of the causes of overheating, and during the past year he has worked on the problem. Until recently, the writer was not aware of the scale on which the problem was being attacked by other investigators and it was a source of considerable gratification to find, on the publication of these papers, that the general conclusions which he had reached concerning the nature of overheating were so nearly correct.

It is not proposed here to enter into any critical discussion of the results of the various experiments, except in so far as further or confirmatory evidence for one or other viewpoint can be given.

Part of the writer's investigation covered the influence of overheating on mechanical properties, particularly the effect of overheating on the endurance limit of En 24 steel made in the basic electric furnace.

The endurance limit under reversed stresses of normal En 24 steel was first determined using a 30-cwt. Haigh fatigue machine and was compared with the endurance limit of samples from the same cast overheated at 1350° C., at which temperature faceted fractures roughly equivalent to those illustrated in Figs. 21 and 22 of Preece, Hartley, Mayer, and Nutting's paper were obtained. The reduction in endurance limit due to this relatively severe overheating was much less than expected and did not confirm the then-

popular belief that drastic reductions in endurance limit were to be expected if the material was even slightly overheated, as is shown by the following :

	Heat-Treatment.	Endurance Limit.
Sample not overheated.	850° C. O.Q., 650° C. A.C.	±27 tons/sq. in.
Sample overheated at 1350° C.	850° C. O.Q., 650° C. A.C.	±20 tons/sq. in.

Numerous impact tests carried out on overheated and normal material also indicated that the Izod values for slightly overheated material were little affected, which was again a direct contradiction of the current belief. It seems that in some cases the abnormally low Izod values attributed to overheating (without confirmatory tests) should be more properly otherwise accounted for.

These results bear out Preece, Hartley, Mayer, and Nutting's contention that moderate degrees of overheating do not adversely affect mechanical properties to any great extent and certainly not to the extent usually assumed.

It was found that overheated structures could be produced with equal ease in atmospheres of hydrogen and nitrogen and, for convenience, all later work was done in an atmosphere of purified commercial nitrogen. Thus the very common belief that oxidizing furnace atmospheres are necessary to produce overheating is no longer tenable.

The effect of cooling rate from overheating temperatures was not investigated, but the importance of this cooling rate in determining whether or not faceted fractures will be produced probably accounts for the erratic results obtained before air-cooling from the furnace was adopted as standard practice.

The method which has been used recently of determining the minimum overheating temperature differs considerably from any of those published and, since it has the advantage of speed and is fairly accurate, an outline of it may be of interest.

The method consists of placing one end of a cylindrical specimen (of dimensions shown in Fig. Y) in the hot zone of a platinum-wound tube

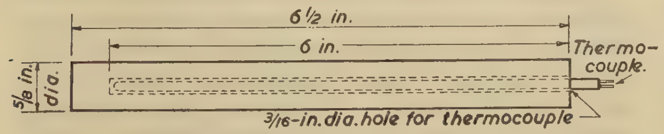


FIG. Y.—Diagram of Specimen and Thermocouple Used in the Determination of Minimum Overheating Temperature.

furnace, heating to a temperature above the minimum overheating temperature, and, by withdrawing the thermocouple ½ in. at a time, determining the temperature gradient along the specimen. After heat-treating (usually oil-quenching from 850° C. followed by cooling from 650° C.) the specimen is split in two longitudinally, and one half is then notched and fractured at ½-in. intervals. By this means the disappearance of facets from the fracture can be located within one of the ½-in. sections. The other half of the specimen is notched at a position midway between the notches on the particular section in which the facets disappear and their disappearance is located within ¼ in. An estimate of the exact distance from the end of the test-piece at which facets just disappear is made and the corresponding temperature read from the temperature-gradient curve.

The estimated maximum temperature error by this method is about ± 10° C. and good agreement can be obtained with duplicate tests.

The usual temperature for the hot end of the specimen was about 1370° C., the cold end being then about 700° C. Greater accuracy would be obtained if the temperature gradient was less steep, but in the particular furnace used this would have involved a specially wound element.

Various etching reagents were tried in an attempt to improve on the nitro-sulphuric reagent and from these a reagent consisting of 10% sulphuric-acid/10% hydrochloric-acid in water was selected as being as good as, if not better than, the nitro-sulphuric reagent. The reageant was used boiling and was most effective on hardened or hardened and lightly tempered specimens. The time of etching varied from 3 to 15 min. and light polishing was usually necessary to improve the contrast. Latterly this reagent replaced the nitro-sulphuric reagent completely and gave quite satisfactory results, although the conditions under which it was used were never particularly exacting and fracture tests were invariably used to settle doubtful cases.

During the examination of these gradient tests one very interesting observation was made—an observation for which, at the moment, no explanation can be suggested, but which may throw some light on the mechanism of facet formation. In one of the En 24 gradient test-pieces which had been heated to 1440° C. at the high-temperature end, a sudden and very marked increase in grain-size occurred at the fifth notch (corresponding to 1365° C.). The increase was very local and in this area the fractured surface consisted of a few extremely large grains, while on each side, although the fractures were heavily faceted, the grain-size was not larger than that anticipated under these conditions of heating.

Mr. A. J. K. HONEYMAN (Messrs. Colvilles, Ltd., Glasgow) wrote : The relationship found between the overheating temperature and the Fox inclusion count is interesting, but it is

unfortunate that other variables, such as composition of steel, ingot size, and degree of hot working have not been taken into consideration; of these, the first two affect the Fox count.

To illustrate, the following experiment was carried out on acid open-hearth silicon–manganese steel which happened to be available. Samples taken from a $2\frac{3}{4}$-in. square, rolled from the middle of a 12-sided, inverted ingot of cross-section approximately 22 in. dia., were forged to $1\frac{3}{8}$ in. dia. Other samples were taken from a small ingot of the same cast, 6 in. long and 2 in. in dia., and were forged to 1 in. square. Samples were heated to 1300°, 1350°, and 1400° C., respectively, for $\frac{1}{2}$ hr., cooled in air, and then oil-quenched, and tempered at 500° C. The Fox count of the first sample (*A*) was 124, large inclusions predominating, while the Fox count of the second sample (*B*) was 99, the inclusions being mainly small.

It was found that the overheating temperature of sample *A* was 1350–1400° C., while that of sample *B* was 1300–1350° C. Both overheated samples gave a white network (Figs. J and K) when etched with the nitro-sulphuric acid reagent (10% sulphuric acid plus 10% nitric acid). This is rather surprising in view of other workers obtaining a black network with this reagent. It is also of interest to note that the sample with the higher overheating temperature also showed white spots. It would be interesting to know if other observers have found these white spots more frequently with higher overheating temperatures.

Tempering to 670° C. for several hours was not sufficient to remove the network entirely but the outlines became faint.

The analysis of the steel was as follows:

Carbon.	Silicon.	Sulphur.	Phosphorus.	Manganese.
0·64%	1·82%	0·036%	0·032%	0·88%

Another interesting point deserving further investigation is the effect of rate of cooling from the overheating temperature. This too, may well be influenced by composition as well as by the overheating temperature.

Perhaps the most significant feature is the response of the boundary network to tempering temperatures after normal quenching. The fact that it tends to disappear at tempering temperatures above 200° C. in low-carbon steel and above 600° C. in alloy steels and that requenching and tempering reproduces it, would seem to indicate, as implied by Preece and his co-workers, that the network arises from diffusion and segregation within the austenite grain. I would venture to suggest, therefore, that the phenomena described may be explained on the hypothesis that it is due to heating the steel within the δ range. The phase-changes in heating and cooling would tend towards segregation in the austenite. Rapid cooling would inhibit migration to the grain boundaries, while very slow cooling would allow of rediffusion.

While little is known of the δ region of alloy steels, the foregoing is offered as a suggestion which may be useful in planning further research.

Mr. H. Evans (The Mond Nickel Co., Ltd., Birmingham) wrote: I would like to convey my appreciation to the various authors of the very interesting and informative papers which have been presented on the complex and important subject of overheating in wrought steels. It may be of interest to set down at this stage some results obtained on steel castings which fall, to some extent, into line with Woolman and Kirkby's hypothesis that overheating in wrought materials is influenced by the cast structure.

Recently I had occasion to examine a fractured sample taken from the centre of a large, heat-treated, $3\frac{1}{2}$% nickel–chromium–molybdenum steel casting. Part of the fracture in this piece had a coarse, faceted appearance (Fig. L), very similar to that in the fractured surfaces of overheated components. The cooling rate at the centre of the casting had, of course, been extremely slow and it was found possible to reproduce the abnormality in laboratory castings by cooling the steel from the molten state at a slow rate. The appearance of the fractured surfaces of the experimental castings was the same as that in overheated wrought material, whilst the nitro-sulphuric acid etching reagent gave dark-etching boundaries, together with a dark-etching orientated pattern within the grains. A photomicrograph of the fractured surface of a coarse-grained laboratory casting after nickel-plating is shown in Fig. M, and illustrates the partly intercrystalline and partly transcrystalline nature of the path of the fracture, which supports the ideas of Woolman and Kirkby rather than those of Preece and his co-workers, who state that the grains in the fracture of overheated material correspond to the crystal structure developed by suitable etching reagents.

Contrary to the results of Woolman and Kirkby on wrought material, heating samples of the casting in the temperature range 1100–1250° C. for 3 hr., followed by slow cooling or rapid cooling and then by normal hardening and tempering treatments, eliminated the coarse faceted type of fracture. A reduction of the casting by a ratio of 5 : 1 by forging, eliminated completely the abnormal fracture in the hardened and tempered steel.

These rather limited results could bear the construction that the susceptibility of wrought material to overheating is influenced by:

(*a*) The cooling rate of the original ingot.

(*b*) The amount of forging or rolling to which the material has been subjected.

The larger the ingot the slower is the cooling rate, and the probability for coarse grains to be present is increased, though subsequent hot work would progressively break down this coarse structure. The occurrence of a coarse-grained structure on further reheating may well be affected by the ingot size and the amount of hot working to which the material has been subjected. Preece and his co-workers do not mention the size of the ingots from which their test-samples were prepared for the overheating experiments. Is it possible that some of the lack of correlation between the overheating temperature and the variables which they have studied is due to the difference in the early histories of the steels examined?

Mr. K. G. Lewis (Royal Naval Torpedo Factory, Greenock) wrote: The Institute are to be congratulated in having this excellent series of papers on overheating submitted at one time. The work of Austin * was the first of note to deal with faceted fractures and their examination. Since that time, much investigatory work has been carried out, but the general picture remains confused, and a satisfactory explanation of the mechanism of overheating is still required. As an outcome of the present series of papers, a joint statement from the authors concerned on those phases of the subject which are agreed upon would be most welcome, as would definitions of the various aspects of overheating. It would appear that "pseudo-overheating" or some similar term is now most necessary.

When all the papers are considered collectively, two features call for criticism. Firstly, at least seven etching reagents have been used, comparison of structures consequently becoming difficult in certain instances. Secondly, and probably more important, most of the steels are of the low-alloy type used to-day for high-duty forgings and are covered in the main by three or four standard specifications. In most cases, they would appear to have been drawn from production and, while examination of such steels would have formed an excellent concluding stage to this very difficult problem, it would surely have been preferable to have controlled certain of the composition variables in the strictly investigatory stages of the examination.

Mr. Preece and his colleagues have admittedly adopted a more suitable technique, namely, statistical correlation, but, for the reason already stated, this has of necessity been conducted over a limited composition range in most instances. Nevertheless, the markedly indicative and positive correlation coefficients for sulphur or oxygen are not necessarily true, since the effect ostensibly due to either element may be associated with some other additional factor which is actually causing variation in overheating temperatures. Any doubt of this nature, however, can readily be decided by calculating the appropriate partial correlation coefficients.† By this means, the effect of sulphur (or oxygen) on overheating temperature can be determined with any other additional factor (or factors) held constant. Thus, instead of the simple correlation coefficient between sulphur (S) and overheating temperature (T), r_{ST}, we have the partial correlation coefficient, $r_{ST \cdot X}$, in which X is an additional factor, maintained constant. It is equally permissible to have higher-order partial correlation coefficients, *e.g.*, $r_{ST \cdot XYZ}$, but it is not considered that a partial coefficient above the first order need be considered in the present instance.

Since all the investigators agree that the steel manufacturing process has a definite effect on overheating temperature, only the basic electric steels from Table III. of Mr. Preece's paper were examined. The number of steels was 20 and, while the coefficient for sulphur, $r_{ST} = +0{\cdot}636$, was confirmed, the coefficient for oxygen, $r_{OT} = +0{\cdot}127$, could hardly be regarded as significant. Attention was then confined essentially to the effect of sulphur and the following partial correlation coefficients were obtained: $r_{ST \cdot O} = +0{\cdot}628$ and $r_{OT \cdot S} = -0{\cdot}028$. It would seem, therefore, that the influence assumed to be due to sulphur on overheating temperature is more or less correct and that oxygen has little or no direct or indirect effect in the case of the basic electric steels examined. The one element outstanding, which could possibly influence the effects due to sulphur or oxygen, was, of course, manganese, but the factors, $r_{MnT} = +0{\cdot}153$, $r_{MnS} = -0{\cdot}235$, and $r_{ST \cdot Mn} = +0{\cdot}699$, provide additional assurance that sulphur is exerting a more or less individual effect in the case of basic electric and also open-hearth steels (*see* below).

In the above calculations, Mr. Preece's positive significance for oxygen is in no case confirmed, but, according to his remarks on p. 246 P, he determined his correlation coefficients on a mixed collection of electric (the above 20) and open-hearth (9 in number) steels—surely a doubtful procedure in the light of his own remarks and those of other investigators. The positive factor of 0·57 for oxygen, however, must be accounted for and, when the factors obtained above are con-

* G. W. Austin, *The Iron and Steel Institute*, 1936, *Special Report No.* 14, p. 189.

† *See*, for example, C. H. Goulden, "Methods of Statistical Analysis," p. 80. London, 1939: Chapman and Hall, Ltd.

sidered, it can only be concluded that oxygen in open-hearth steels has a marked positive effect on the overheating temperature. In any case, this conclusion is only in line with the known higher oxygen content of open-hearth steels and their higher overheating temperatures, the latter having been amply demonstrated by Mr. Preece and his colleagues.

It is logical to assume that the steels with a high inclusion content will have a high oxygen content, so that Mr. Preece's findings of high overheating temperatures would be confirmed statistically in the case of open-hearth steels. His work is of the greatest value in providing firm proof that overheating is not the result of envelopment by the fusion of non-metallic constituents. But, it is thought, this proof should be regarded, for the moment at any rate, as applying only to steels of open-hearth origin. At the same time, it is not thought that the inclusion theory can apply to basic-electric quality steels, where the oxygen content and inclusion count are generally so low as to preclude the possibility of anything like continuous envelopes of non-metallic films. It is agreed that precipitation of any agency along *all* grain boundaries does not appear to be necessary and both Merchant's and Woolman and Kirkby's papers draw attention to fractures which are only partly faceted. Do not the latter investigators regard the reference to "austenitic grain-size at the reheating temperature" as being somewhat dangerous without further qualification? The inherent grain-size of the material may be exerting some effect, quite apart from that due to reheating temperature.

Messrs. Woolman and Kirkby remark that the facet fractures corresponded with the grain-size obtained by micro-examination, a statement which must draw attention to the confused state of affairs regarding aluminium addition, since they state earlier that increased aluminium additions resulted in increased grain-size for a given temperature. Quite the reverse condition would normally be expected and it would be of interest to know whether these authors have ever experienced such a result in the instance of a plain carbon steel, or, at any rate, a steel of strictly low alloy content. One remark in their paper does call for further clarification with regard to the aluminium content. The authors state: "The additions of aluminium to each individual ingot . . . were . . ." and then proceed to record a percentage figure for the aluminium content and, again, in Table VI. they show three identically similar aluminium contents in numerous samples. It would be logical to ask, therefore, if they are recording the aluminium added as a percentage of the ingot or cast weight. If so, as would appear to be the case, it is quite unjustified, since conditions of temperature, oxygen in steel, and slag, &c., must be controlling factors. Two heats of almost identical composition cannot be expected to respond in an identical manner to equal aluminium additions. Further, is the aluminium regarded as existing in the steel in the soluble form, or as alumina, or as both? The writer's experience with regard to plain carbon steels has been that the marked degree of heterogeneity of both soluble aluminium and alumina which persists over an ingot, over a plate of ingots (*e.g.*, in bottom-casting practice) and over a cast, is such that aluminium content, in whatever form or forms it may exist, calls for most careful examination and definition. In low-alloy steels, the aluminium addition is in general much smaller, but the degree of variation is certainly as great as in plain carbon steels. The remarks on heterogeneity will apply also to gas content, a feature to which Professor Thompson has drawn attention.

Messrs. Woolman and Kirkby appear to have made their initial additions of aluminium to the furnace bath, followed in certain instances by additions to the mould. In the former case, the condition of the heat must determine the amount and form of aluminium taken up by the melt, and only a small amount (at any rate, of alumina) can be expected to remain in the metal at the time of tapping, a remark that will apply in even fuller measure to heats of acid steel. Additions of aluminium to the mould are generally fraught with inconsistency, unless considerable agitation of the steel can be effected. Even under conditions of bottom-teeming practice, where the aluminium is swept along in the metal stream, inconsistencies with regard to aluminium have been observed. It is surprising that the authors have not confined aluminium additions to the ladle, a procedure which they have adopted (in part) in the second stage of series (experiment (10)).

Little has been said in most of the papers regarding the method of forging and the degree of punishment applied to the steel during the forging operation. The remarks of Woolman and Kirkby, however, are of the greatest importance with regard to "temperature plus forging" and would have been of even greater value if they could have been recorded on some quantitative basis. Have these authors any information on the behaviour, with reference to the initiation of faceting and to the size of facets, on steels which have been heated to the same temperature ranges, but which have been subjected to varying degrees of forging?

It is unfortunate that contrary results have been obtained regarding rates of cooling, regarded by many people as the factor controlling the incidence of the faceting phenomenon. But the results of Mr. Goodrich and those of Messrs. Woolman and Kirkby point to lack of agreement on this issue. The former draws attention to the effect of tem-

pering temperature, but, as Mr. Goodrich well knows, users of low-alloy steel forgings will always require material tempered at the higher temperature ranges in order to obtain optimum mechanical properties.

In conclusion, it is very evident that marked differences of opinion still exist regarding certain of the factors affecting the overheating of steel, and that the wealth of data submitted by the various authors have only succeeded in eliminating a few of the possible agencies. All the papers, however, constitute a valuable initial contribution in attempting to isolate the cause or causes of trouble due to overheating—a danger which of necessity must be given much further study when the requirements of high-duty steel forgings are considered.

Mr. L. Fine (Menasco Manufacturing Company, Burbank, California, U.S.A.) wrote: As Preece and his co-authors have mentioned, an ordinary etch does not reveal the presence of overheating. Fig. N shows a sample of drill rod which was heated to 2500° F. in air for 10 min., air-cooled, reheated above Ar_3, quenched, and tempered at 800° F. When polished and etched in nital, it showed no indication of overheating, but on re-etching in an electrolytic phosphoric acid solution,* the presence of the prior austenitic grain boundaries was clearly revealed, as in Fig. O, which shows the same area of the same sample. The phosphoric acid etch acts similarly to the nitro-sulphuric etch.

In regard to the restoration of overheated steel by slow cooling, the following corroborative evidence may be presented. Three samples of NE 8735 were heated at 2600° F. in air for 5 min. each. The first sample was oil-quenched, the second air-cooled, and the third furnace-cooled to 2350° F. and then air-cooled. The samples were then reheated above Ar_3, quenched, and tempered at 900° F., polished, and given an electrolytic phosphoric acid etch. Figs. P, Q, and R represent the quenched, air-cooled, and furnace-cooled specimens respectively, and it can be seen that the furnace-cooled specimen barely reveals any intergranular pattern. However, the writer would like to point out that in his experiments the quenched samples did not appear better than the air-cooled ones.

Mechanism of Overheating.—Some time ago it was observed by the writer and his co-workers, Maak and Ozanich, that there was a striking similarity in the behaviour of the weld-plane of a pressure weld and that of overheated austenitic grain boundaries. A sample of a pressure weld in S.A.E.4340 steel was purposely overheated in welding, so as to produce an overheated-grain pattern in addition to the weld-plane pattern. Two sections of the sample weld, ½ in. apart, were then reheated to 2530° F., one being air-cooled and the other furnace-cooled, *see* Figs. S and T respectively. It can be seen that the improvement in the weld-plane characteristics and of the overheated-grain pattern have proceeded to an almost equal degree. Further, it was observed that slow cooling from certain high temperatures would effect complete disappearance of the weld-plane and overheated-grain patterns. If, to this evidence, one adds the fact that in both cases it was not possible to observe anything after an ordinary etch and that the electrolytic phosphoric acid etch worked equally well on both, the similarity becomes truly striking. The line of pits revealed by the phosphoric acid etch in a pressure weld is attributed by the writer and his co-workers to the presence of submicroscopic voids. Further experimentation has led the writer to believe that the same is true of the pits found along the boundaries of overheated austenitic grains.

As the authors have stated, the type of atmosphere does not appear to have any bearing on the extent of overheating. The writer has heated samples in hydrogen, in nitrogen, in argon, in oxygen, in air, and in a vacuum, with identical results. The oxygen atmosphere, owing to the rapid formation of iron oxide, had a tendency to heat the sample above the furnace temperature and this point had to be carefully watched.

The writer cannot accept the authors' statement that "the mechanism of overheating must therefore involve a diffusion process within the austenite grain. It is not clear what the diffusing element or elements are, nor whether diffusion is to or from the boundary." To begin with, the authors have stated that small specimens show evidence of overheating after only 5 min. exposure to high temperature. The writer has noted that 1½ min. at high temperature have been sufficient to produce an overheated-grain pattern, and that many welds (particularly those made in S.A.E. 4340 type steel) will show overheated-grain patterns in the heat-affected zone of the weld,† which could have been at temperature for only a few seconds. Since diffusion is a process involving considerable lengths of time, it would appear most improbable that any element, with the possible exception of the very light elements, would diffuse either to or from the grain boundaries so rapidly. Further, when true burning

* The electrolytic phosphoric acid etch, originally developed by the writer and his co-workers for use in the examination of pressure welds, is discussed in "Fundamentals Affecting the Bond in Pressure Welds," by L. Fine, C. H. Maak, and A. R. Ozanich, *Journal of the American Welding Society*, 1946, vol. 25, June, p. 519.

† Incidentally, this can be a contributing cause for the poorer physical properties attributed to the heat-affected zones in arc welds.

sets in, the overheated-grain pattern disappears and is replaced by large voids occurring between the grains; if diffusion actually took place, one would expect the accentuation of the reaction and not its disappearance at higher temperatures.

The writer believes that the submicroscopic-void theory is more consistent with the evidence. For example, when burning or melting * occurs, it would be anticipated that the submicroscopic voids would disappear, owing to surface energy forces, † and be replaced by large voids such as are present in poor-quality castings. It may also be pointed out that if a pressure weld with a line of pits developed by the phosphoric acid etch be heated well into the overheating range and air-cooled, the line of pits at the weld-plane will disappear, and a series of pits will occur around the prior austenitic grain boundaries. It is believed by the writer that the submicroscopic voids disappear from the weld-plane because the high temperature decreases the plastic strength of the material sufficiently to permit complete ‡ closure by surface-energy forces. However, although the same forces are at play at the austenitic grain boundaries, some other reaction is occurring which counteracts their effect. A possible hypothesis is that in the overheating-temperature range melting begins at the grain boundaries at a much lower temperature than within the body of the grains; these minute molten particles of material expand in melting, causing the grains to become slightly separated, and upon subsequent cooling and solidification leave a series of submicroscopic voids in the grain boundaries. This hypothesis nicely fits the fact that slow cooling eliminates the overheating effect, whereas faster cooling increases it. One can logically reason that in slow cooling, after the molten particles resolidify, the surface-energy forces can come into play and cause closure of the voids if given sufficient time.

This hypothesis can also explain why, when burning or melting occurs, the pits disappear. If, in addition to the grain boundary, portions of the grain itself begin to melt, it appears reasonable to suppose that the molten particles at the weld-plane would unite with the molten portion of the grain and act as a unit, which upon solidification produces macroscopic voids generally surrounding the grain boundaries. These large voids can be expected, because, as pointed out by Jominy, the internal portion of the steel can melt while the outer surface remains solid owing to its higher melting point due to decarburization. This internal melting causes a large increase in volume and the molten material does not resume its former size on cooling, since the outer surface is never molten and forms a hard, solid shell into which the inside must accommodate itself. Since the inside upon solidification will occupy a much smaller volume than that available, it is to be expected that voids will form and, since solidification proceeds outwards from the grain centre, that they will surround the grain boundaries, as in Fig. U; in this example some of the voids were extremely large and were visible before etching.

Overheating versus *Burning of Steel.*—It follows from the foregoing that a burnt steel is one that has undergone melting not only at the grain boundary but also in the body of the grain. It will show voids visible under the microscope without etching; they may be located only at the previously existing grain boundaries. Among the metallographic characteristics of burnt steel is the disclosure of the prior austenitic grain boundaries in a nital etch as shown in Fig. V, or in an alkaline chromate etch as shown in Fig. W, and often a diffusion of the inclusions to the grain boundaries (if sufficient time at burning temperature is permitted) as shown in Fig. X. Some diffusion of the inclusions can also occur in overheated steels, but the temperature is usually too low for their rapid movement. Other common characteristics of burnt steel are porosity, a dendritic pattern, and segregation of alloying elements. The principal indication of burning is, however, the presence of large voids.

Burnt steel cannot be repaired by heat-treatment alone, since the closure of large voids is impossible; it must be reforged.

Overheated steel, on the other hand, cannot be detected under the microscope except by using special etches, such as the nitro-sulphuric etch and the electrolytic phosphoric acid etch (and possibly several of the others mentioned by the authors). Overheated steel should not show any microscopic voids and should be free from intergranular precipitation of inclusions. Overheated steel, if it is not partially burned, can be repaired by heat-treatment alone. It should be remembered that the transition from a steel at high heat through one at overheat to one at burning temperatures is gradual and that one must use discretion in making a decision. It certainly is possible to have all three conditions present in different parts of even a small sample.

* The terms burning and melting can be used synonymously, as Jominy pointed out in his excellent work on this subject.

† Fine, Maak, and Ozanich, *loc. cit.*

‡ The word " complete " is used here in its practical sense. Theoretically, " complete " closure cannot take place until melting occurs.

AUTHORS' REPLIES.

Mr. MERCHANT wrote in reply: Dr. Jenkin has suggested that the evidence in my paper for the effects of time and atmosphere on overheating is not conclusive. With regard to the effect of time, I intended to imply that this was important from a practical point of view in heating steel for forging. For instance, Mr. Preece and his co-workers have shown that there is a wide variation in the overheating temperature of different casts of steel, even of the same specification; they have also shown (*see* Figs. 27 and 28 of their paper) that soaking time has an appreciable influence on facet size; thus it is obvious that steel with a low incipient overheating temperature will respond to the effect of undue soaking time at what have hitherto been considered normal temperatures for heating for forging.

With regard to the effect of furnace atmosphere, recent researches have shown that this has no effect on the overheating properties of steel, but Mr. Goodrich's suggestion that a strongly oxidizing and turbulent atmosphere results in hot-spots in the furnace is a point to be well watched in preventing overheating.

Mr. Preece mentioned that he had not seen coloured films on overheated fractures; I have seen these films on newly fractured overheated specimens quite often, but they sometimes appear to fade quickly with time.

Mr. Preece also thought that "crozzling" is of very doubtful value for assessing overheating. I agree that it indicates mainly the grain-size obtained by the austenite during heating, but surely such grain-sizes as those of the order of 0 to −3 (A.S.T.M. grain-size number) are an indication of excessive grain growth and probable overheating. The "crozzling" test has its disadvantages, and is not conclusive, but it is still the only non-destructive test which gives an indication of overheating. During the war it was satisfactorily applied as a pre-selective test for overheating by the leading aircraft manufacturers in Great Britain.

Neither Dr. Jenkin nor Mr. Preece favours the use of fracture standards. It is agreed that there is a wide variety of granular fractures which can be produced according to the overheating properties inherent in the steel, with a consequently widely different effect on the embrittlement of the steel. Nevertheless, under the stress of war conditions, standard fractures were more or less satisfactorily employed both in Britain and in the U.S.A. for determining freedom from detrimental overheating in drop-forgings. Unless steel can be produced with a known and guaranteed high incipient overheating temperature, the testing of each cast for susceptibility to overheating, and the checking in consequent production, with all its elaborations, must become a routine matter for the manufacturers of high-quality steel drop-forgings.

I was very interested to see that both Mr. Preece and his co-workers and Messrs. Woolman and Kirkby reported some experiments on the effect of forging on overheated steels. Although both groups of workers conducted experiments on material heated 75° C. above the incipient overheating temperature, the results obtained differ somewhat in that Mr. Preece and his co-workers found evidence of overheating after forging, whereas Messrs. Woolman and Kirkby concluded that the effect of forging is apparently to raise the overheating temperature some 75–100° C. in the steel they used. Their conclusion is in line with my experience, and from a practical point of view the importance of sufficient hot-work cannot be stressed too much. However, I would like to suggest that some research be undertaken on the effect of light amounts of forging, such as would effect less than the equivalent of a reduction of area of 30%.

With reference to Mr. Hartley's comments on my suggestion that overheating could not be caused by a transient increase in temperature on forging, it is thought that the good effects of hot-work in reducing or eliminating overheating would probably more than off-set any ill effects due to such a transient increase in temperature.

I was somewhat disappointed to find no mention in the other papers of the effect of overheating on the fatigue properties and, apart from some useful work by Mr. Preece and his co-workers, little mention of the ordinary static mechanical properties. The information supplied in the discussion by Mr. Hinde and Mr. Frith on the fatigue life of overheated connecting rods was therefore very welcome. Fracture tests and metallographic examination may be very useful in detecting overheating, but due regard should be paid in any future work to the mechanical properties, which are, after all, still the main criteria of serviceability.

Mr. PREECE, Mr. HARTLEY, Mr. MAYER, and Mr. NUTTING wrote in reply: We wish to thank all those who contributed to the discussion. The large number of contributions is encouraging and at the same time indicates the importance of the subject.

In writing our paper we resisted the temptation to theorize and confined ourselves to a statement of experimental results. No conclusions were made unless they were clearly indicated; we cannot, therefore, accept Dr. O'Neill's

final reference to a "delightful vagueness of the papers."

We think the statement by Mr. Goodrich that "rapid cooling through the upper critical range was necessary to produce the granular type of fracture," is misleading. There is nothing fundamental in this rapid cooling, and with certain compositions of steel the characteristic fracture can be produced without it, as shown by Mr. Woolman and Mr. Kirkby.

Replying to Mr. Goodrich's contention that he would have expected a greater degree of overheating on prolonged soaking, we would emphasize that this development of the overheated structure should be considered as a diffusion process taking place, not at a constant temperature, but during the cooling through the overheating range. We have shown that the rate at which this cooling takes place has a profound influence on the diffusion, and would quote our experiments on resuscitation as evidence.

The main difficulties in accepting Woolman and Kirkby's precipitation theory are :

(1) The complete absence of experimental evidence to support it.

(2) The number of further assumptions that have to be made when their theory is used to explain experimental results.

(3) The failure of the theory to explain the response of overheated steels to tempering effects.

We disagree with Mr. Woolman and also with Professor Thompson and Dr. O'Neill who interpret Fig. 5(*d*) in our paper as evidence of a correlation between nitrogen content and overheating temperature. A statistical examination of the plots in Fig. 5(*d*) gives a correlation which cannot be regarded as significant. We therefore see no reason why we should not adhere to our original statement. We also think that the evidence in Table II. in Woolman and Kirkby's paper, and referred to by Dr. O'Neill, is quite insufficient for any valid conclusion regarding the effect of nitrogen.

Concerning Mr. Woolman's statement on the influence of oxygen and sulphur on overheating, we think that the important factor here is not so much the actual solubility, but rather the change of solubility with temperature.

In considering Professor Thompson's argument that overheating can, in some undefined way, be ascribed to a concentration of gas at the austenite boundaries, it is difficult to account for the results obtained with steels of a high oxygen content. It is problematic also that sulphur dioxide would be formed in preference to carbon monoxide by the action of the respective elements with ferrous oxide since it is known that carbon will burn in sulphur dioxide. Also, when sulphur dioxide and ferrous oxide are brought together at high temperatures, a reaction occurs in which sulphur and ferric oxide are formed.

Dr. Sutton has raised a very important practical point with regard to the influence of case-hardening in masking the overheated condition, especially in connection with fatigue properties. It is unfortunate that so little information is available on this particular subject.

Electromagnetic tests have been found to be unsatisfactory for detecting overheated steels, but the magnaflux method will indicate burnt steels where intergranular oxidation has produced discontinuities in the surface.

The fact that Mr. Hinde did not find a single service failure that could be attributed to overheating is further evidence in support of our results, which showed that an appreciable degree of overheating could take place before the mechanical properties of the steel were seriously affected. This fact emphasizes the need, not so much for a test to detect overheating, but rather to indicate just when the overheating has reached a stage where deterioration in the mechanical properties is important.

In agreement with Mr. Hinde's results we also found that with some specimens of burnt steel the nitro-sulphuric etch gave white boundaries. One specimen was rather interesting in this respect : It gave white boundaries with nitro-sulphuric acid in the as-cooled condition, but after heat-treatment the normal black boundary structure was apparent. It is interesting to note that this specimen also gave similar results with the nitric-acid/picric-acid reagent, but with ammonium nitrate, heat-treatment had no influence, the boundaries being black in both conditions.

Mr. Frith's contribution is most valuable, providing much needed information on the fatigue performance of overheated steels. We hope that he will continue this work and publish his findings in due course.

We welcome the contribution from Professor Austin and wish to acknowledge the help obtained from his earlier publication.

Thanks are due to Professor Bastien for his clear description of the various stages of overheating. Our results on resuscitation, which show that slow cooling (3° C./min.) or quenching through the overheating range tends to suppress overheating, answer in part the question he raises on slow cooling.

Mr. Bucknall seeks an explanation of overheating on the basis of δ-ferrite precipitation, but it would be surprising if the δ zone extended to the lower overheating temperatures.

The point raised by Dr. O'Neill regarding the correlation between nitrogen content and overheating temperature has been dealt with earlier. Through the kindness of Mr. Burns, of the

Admiralty Engineering Laboratory, micro-hardness tests have been carried out on overheated steels using a 100-g. load, but unfortunately the results were received too late for inclusion in the paper. They showed, however, no difference in the hardness between the boundary and the remainder of the grain.

Dr. Waterhouse referred to a paper by Jominy and Strohm. We had not had an opportunity of reading it before our own paper was published but have now done so and find that our own results are generally in agreement with those of the American workers.

In reply to Mr. Cooper we would say that a solution of this problem of overheating is proving very difficult as there are so many variables which might interfere but which are not easy to eliminate. In our own work we have examined almost a thousand specimens which have been treated under very carefully controlled experimental conditions and even after this vast amount of experimental work we are still unable to give a satisfactory explanation.

We thank Dr. Desch for drawing attention to the use of conical illumination for revealing the flow lines due to incipient fusion; we have not yet used this method. We have tried electrolytic polishing on a number of specimens but so far it has not shown any particular advantage.

We failed to obtain a structure on overheated steel with the chromate etching reagent referred to by Mr. Meikle; some progress is, however, being made with an alkaline chromate and permanganate reagent described recently by Hall.*

We thank Dr. Norbury for pointing out the excluding feature in connection with the two exceptions in Fig. 6. We appreciate his keen interest in our work.

Mr. Burns has drawn attention to certain steels in which overheated structures were not developed at temperatures below that at which burning occurred. These steels are most important and are being carefully examined, but, though the evidence so far obtained suggests that these steels cannot be overheated, the examination is not yet complete.

The occurrence of overheated structures in flash-welded sections is not surprising even under conditions of rapid cooling, as the latter is not as effective as very slow cooling in suppressing the development of the overheated structure.

A comparison of grain growth and overheating characteristics as suggested by Mr. Burns should prove very interesting and will be examined as soon as opportunity permits.

It is not quite clear from Mr. Kirkby's contribution whether the variation in the clearness of the structure obtained in the nitro-sulphuric etch refers to specimens of the same or of different steels. We found wide variations from steel to steel but not with specimens from the same bar. It has been noted, however, that the boundary structure is more clearly developed by this etchant when the steel is slightly deformed or cold-worked before etching.

While acknowledging the importance of a normalizing treatment as described by Mr. Kirkby, the fact that there was no change in the Izod values of steels heated below the overheating temperature (even when the latter was above 1375° C.) is evidence that grain growth in this particular instance has had no influence. Consequently these figures would not be modified by the treatment described by Mr. Kirkby. It is agreed, however, that in cases where coarse structures are experienced it would be necessary to carry out such a treatment.

We do not agree with Dr. Colombier's statement that considerable grain growth is necessary before the nitro-sulphuric etchant reveals the structure. We have satisfactorily etched very fine overheated structures obtained in tests with less than five minutes' heating.

We support in full Dr. Colombier's happy reference to future collaboration across the Channel.

The contribution from Dr. Kondic and Dr. Wheeler is of interest. We would explain that the appearance of the fracture obtained in the as-heated condition cannot be taken as a test for overheating as the steel must be toughened by appropriate heat-treatment. In the particular case quoted we would ask "Can the 40% decrease in elongation and reduction of area be attributed to grain growth?"

Mr. Walker's method commends itself to us as a rapid and simple way of determining the minimum overheating temperature. We think that it could be used most effectively as a routine test in a works laboratory.

The coarse structure obtained at 1365° C. is difficult to understand. We have carried out a large number of experiments on grain growth in these temperature regions, but have not experienced anything of that nature in our work.

The "white spots" referred to by Mr. Honeyman are found in steels which have been heated to very near the burning zone. A non-metallic inclusion is almost invariably found at the centre of these white areas.

We agree that ingot size has an important influence on the distribution and size of inclusions. Apart from heterogeneity produced during solidification, the more rapid cooling of the smaller ingot, even after solidification, would result in a finer sulphide particle. The steels used in the present investigation, with a few exceptions, were rolled from ingots which varied

* A. M. Hall, *Metal Progress*, 1946, vol. 50, No. 1, p. 92.

in size from 25 to 29 cwt., and where it was possible to compare two steels of the same sulphur content, but with the difference in ingot size quoted above or even with a variation of from 25 to 35 cwt., the inclusion counts were similar.

In our opinion, the photomicrograph (Fig. M) shown by Mr. Evans, does not invalidate our views regarding the correspondence between the grains shown by the fracture and the etched boundaries. Our contention does not mean that the fracture must be intergranular along its whole length and breadth. The path followed by the fracture will surely depend upon the irregular nature of the boundary and its relative weakness, and unless the latter is very great there will be occasions when the line of least resistance will cut through the grains.

While agreeing with Mr. Lewis that the general term "overheating" does not properly define the structural changes which take place, we consider "pseudo-overheating" equally unsatisfactory.

Mr. Lewis deprecates the use of seven etching reagents but, surely, in dealing with these unusual and incompletely understood structures the very fact that they can be revealed by different etching reagents is an advantage.

In considering evidence obtained by a statistical examination of results so far obtained, we have drawn attention to the limited number of observations available. From our calculation of partial coefficients we did not feel justified in concluding that the oxygen content of the steel could be neglected. We thought it inadvisable to separate the open-hearth and electric steels, since we had found as wide a variation in overheating properties in each as between the two kinds.

We were interested in the micrographs obtained by Mr. Fine in his work on welded structures. We do not agree with his conclusion that the austenitic boundary of overheated steel consists of a series of sub-microscopic voids, and draw attention to the continuous boundary revealed by the ammonium nitrate etchant as evidence in support of our views.

Mr. Fine's difficulty in accepting the diffusion theory would be overcome if it were appreciated that the diffusion occurred not at the soaking temperature but during the cooling through the overheating range.

Mr. Goodrich wrote in reply: The quality and quantity of the contributions to the discussion of the papers submitted is very gratifying. So many useful views and suggestions were expressed that it is impossible to discuss them all without embarking on a lengthy dissertation. I was, however, particularly interested in the comments of those contributors who made reference to the correlation of fatigue strength and degree of overheating or burning, particularly the data submitted by Mr. P. H. Frith in connection with the investigations carried out in the laboratories of the Bristol Aeroplane Co., Ltd. From the photographs accompanying his contribution we should definitely classify grades *E* and *F* as so grossly overheated that they could be justifiably referred to as burnt; even grade *D* would appear to be at least grossly overheated. It is possible that Mr. Frith had himself come to this conclusion, as towards the end of his contribution he states that it was decided not to carry out any more tests with grades *E* and *F*. Keeping this view in mind, therefore, it is of considerable interest to observe that the steel can be in a distinctly overheated condition and yet show no marked deterioration in fatigue properties.

Professor Bastien's comments were of considerable interest and in most cases coincide with my own views. I would, however, like to point out that where he quotes me as indicating "that comparatively rapid cooling in the upper critical zone is necessary for the development of the type of granular fracture in question" he has not differentiated between the bright granular fracture depicted as *D* in Fig. 1 of my paper with the dull grey granular facets of fracture *E* in Fig. 1. These latter facets are those customarily encountered when dealing with overheated material and we consider that for their formation comparatively rapid cooling through the upper critical zone is necessary.

Mr. E. H. Bucknall's reference to the possible influence of precipitated δ ferrite partly expresses what I had in mind when I referred in the paper to the possibility of a phase-change being a contributory feature towards the formation of an overheated structure, rather than incipient fusion or precipitation of some constituent at the grain boundaries. In this connection it would be of considerable interest to ascertain the extent to which the temperature of the first appearance of δ ferrite is affected by the presence of non-metallic inclusions.

With reference to Dr. G. B. Waterhouse's contribution, I quite agree that present evidence indicates that if the zone of the solidus is reached, burning results. I do, however, think he has made a wrong assumption when he states "I rather think these authors feel that the overheating has caused some action at the grain boundaries which cannot be overcome by subsequent heat-treatment." I am sure we are all agreed that the faceted fracture of overheated material can be eradicated by further forging and repeated heat-treatments but neither of these processes will restore burnt material.

I am in general agreement with most of Mr.

H. W. Kirkby's remarks, but I must take exception to the first of his two definitions of overheating. According to this, a forging soaked for a long enough time at a few degrees above the upper critical temperature would be classified as overheated.

In Mr. A. Hartley's written contribution he states that I find the electrolytic ammonium nitrate etchant unsatisfactory. What I actually said was that I did not find it gave consistently satisfactory results by comparison with 2% nitric acid or 10% nitric and 10% sulphuric reagents. I was glad to notice, however, that he agreed that the 2% nitric acid reagent gave white boundaries and white pools in the interior of the crystals of overheated steel in the air-cooled condition and that those boundaries and pools appear to etch dark in tempered specimens. This confirms my own evidence, but I can assure Mr. Hartley that it can be produced with overheating temperatures even below 1400° C.

In conclusion, I would like to take this opportunity of thanking all the contributors to the discussion, not only for their remarks but also for the interest they have shown in the papers submitted.

Professor THOMPSON and Professor STANTON have no reply to make.

Mr. WOOLMAN and Mr. KIRKBY wrote in reply: The interesting discussion which the various papers have provoked is an indication of the importance of the subject, and illustrates the demand for an improved understanding of the phenomenon of overheating. We had endeavoured to trace certain factors involved in the process of overheating and we feel that our results are illuminating in several respects. With regard to Dr. Jenkin's opening remarks (several others have also raised the point), it was not true to say that we were reluctant to accept Mr. Preece's refutation of any correlation between the actual austenitic grain-size and incipient overheating temperature. We confirm this lack of correlation in our section (9), and Mr. Preece also agrees with our section (6) (*d*) in that the austenitic grain-size, the facet size, and the network size in the etched structure appear to be identical. That size, however, bears no relation to the minimum overheating temperature. It is possible that the misconception has arisen from the arguments put forward on p. 270 P which gave rise to the subsequent experiments.

There is little in Mr. Preece's results and conclusions which are not in agreement with our own. As regards our theory of the grain-boundary precipitate, the fact that it has not been seen may be due in general to its extreme fineness, although grain-boundary inclusions are sometimes observed in very severely overheated structures. Also, the fact that the grain boundaries sometimes appear to have appreciable width when etched in certain reagents (a statement also made by Mr. Goodrich) is not antagonistic to the theory and is merely an etching effect. A similar phenomenon is sometimes observed in over-etched austenitic steels in a highly susceptible condition for intercrystalline corrosion which is also a phenomenon associated with grain-boundary precipitation. An alternative explanation is that the wide etched zone may represent the zone from which the precipitate has been derived. As regards Table I., the results of which Mr. Preece considers unexpected, we can only offer the explanation already given in the paper.

Professor Thompson's remarks are interesting and we should be prepared to agree completely with him that gases may be playing the part he suggests in the phenomenon of overheating, if it were not for the fact that whatever it is that causes the phenomenon does not make its presence felt at the overheating temperature, but only on cooling from that temperature. If, however, the products of the reactions suggested are soluble at the overheating temperature and less soluble at lower temperatures, precipitation at the grain boundaries might be expected in the manner he puts forward.

We are in general agreement with Professor Bastien, except that we assert that the susceptibility to overheating is not a function of the grain-growth characteristics, albeit that the faceted fractures are related to the actual grains existing at the overheating temperature. As regards the apparent different response of quick cooling in Mr. Goodrich's and in our own experiments, the former are based on fracture tests in the hardened condition. As previously pointed out, true overheating can only be ascertained by fractures on steel in the toughened condition.

We agree with Mr. Bucknall that it is possible to see faceted fractures five or ten times the actual grain-size of the finished product, or of the austenitic grain-size as determined by the McQuaid-Ehn test. We have tried to emphasize that the faceted size corresponds to the grain-size at the actual and overheating temperature, and that any subsequent refining treatment, whilst affecting the final grain-size, does not obliterate the previous boundary material or whatever it is that is responsible for the faceted fracture.

Mr. Bucknall's suggestion that the δ phase may play a part in the phenomenon of overheating is interesting, but it is hardly feasible, since it cannot explain the overheating which occurs in, say, 1·4% carbon steel where δ ferrite is not formed. Even if δ ferrite were formed it would not explain the persistence of facets when samples are well soaked at temperatures well below the δ range.

We do not understand Mr. Cooper's comments. He will find much that is new in the papers submitted and it should be pointed out that, whilst certain facts regarding overheating were suspected four years ago, they had never been definitely established and some things which were thought to be important at that time have now been proved to have no bearing on the subject.

Dr. Wrażej appears to be confusing overheating as judged purely by grain-size and that revealed by faceted fractures. With regard to the avoidance of a critical degree of forging and temperature, this is best ensured by not using too high a temperature of reheating for forging and by not finishing the forging at too high a temperature. An initial forging temperature that is too high may give rise to faceted fractures, whilst a high finishing temperature, if below the overheating range, would produce a coarse "as-forged" grain-size.

We have tried the reagent mentioned by Mr. Meikle on several samples which had shown a positive response to the nitro-sulphuric etch, but it did not reveal any abnormality.

The discrepancy referred to by Mr. Hartley between the published equilibrium diagram and our data for minimum overheating for a carbon–chromium steel, calls attention to the inaccuracy of many published equilibrium diagrams of which the chromium diagram would appear to be one.

We were very interested in Dr. Colombier's contribution, but do not agree with him in his rejection of the precipitation theory. It is, of course, easy to visualize a greater concentration of impurities at grain boundaries and it is not even necessary to invoke the action of surface tension in this respect. If, however, this were simply the explanation of overheating, it would not account for the effect of different rates of cooling on the phenomenon. The influence of silicon and phosphorus on the minimum overheating temperature may be explained by their possible effect on the solubility of the precipitate in austenite at various elevated temperatures.

It is doubtful whether a definition of overheating based on the mechanical properties, as suggested by Dr. Kondic and Dr. Wheeler, would be accepted, although this has some attraction from the practical point of view. The difficulty would be in defining the reduction in properties considered as representing the initiation of overheating, since this would have to be determined on material from the same cast which had been given the same degree of reduction in hot working and which had not been subjected to overheating. Our definition of overheating has the merit of being precise. Regarding their remarks concerning two nickel–chromium–molybdenum steels, it is not clear whether the faceted fractures referred to are really due to overheating, since the specimens were no doubt fractured in the hardened condition. As previously emphasized, true overheating can only be determined by fractures of toughened material. Large grain-size itself may adversely affect ductility without evidence of overheating being present.

With regard to Mr. Evans' remarks it is not clear whether faceted fractures on cast material are of the same nature as those on forged material. In some cases they may be so, and the conditions of relatively slow cooling from a high temperature are conducive to precipitation effects, which we suggest are responsible for the faceted fractures. On the other hand, in castings there is always a pronounced heterogeneity of structure which will also tend to produce complications in the fractured surface and give the appearance of faceted fractures. Such effects would be expected to be removed to some extent by heating at temperatures of the order of normal forging temperatures.

Mr. Lewis appears to have misinterpreted our references to effect of aluminium additions. The increase in grain-size associated with aluminium additions at temperatures of the order of 1200–1250° C. should not be confused with inherent fine grain-size which usually results with aluminium-treated steel when heated at temperatures of the order of 900–950° C. Whilst aluminium-treated steel may be fine-grained at the temperature employed for the McQuaid-Ehn test, it may have a coarser grain at higher temperatures than material not grain-size-controlled. As regards Table VI., the figures quoted were percentage additions of aluminium in the ingot. That the influence of aluminium additions depends on the condition of the bath is well known. We assumed that the condition of the steel in the four ingots from the same cast would be reasonably the same prior to the addition of the extra aluminium.

We are not clear as to his reference to the "austenitic grain-size at the reheating temperature." This implies the actual size of the austenitic grains at the temperature and, of course, bears no reference to the so-called austenitic grain-size or inherent grain-size as determined by the McQuaid-Ehn test.

Regarding Mr. Fine's very interesting contribution, it is not possible to comment on his experiments with NE 8735 steel without a knowledge of the actual rates of cooling or the size of the pieces tested. His alternative theory of overheating is ingenious and merits serious consideration, but there is some doubt as to whether it can be justified. In the first place it is difficult to visualize how the pronounced influence of sulphur and oxygen can be explained on this theory. Secondly, it does not explain the prevention of faceted fractures by very rapid quenching from the overheating temperature, a fact which has been definitely established both by Preece and

his co-workers and by ourselves. Again, it cannot explain the results of quenching from different temperatures below the overheating temperature as shown in Table I. of our paper. The effects of the electrolytic phosphoric etch showing pitting at grain boundaries need not be due to voids. It may just as well be due to attack of a precipitate, and Mr. Fine's photomicrograph in Fig. X shows how inclusions may be shown to be present at grain boundaries when the overheating temperature is very high. The fact that such inclusions have been identified as manganese sulphide is most interesting in view of our own indications mentioned at the end of our paper.

THE DETECTION OF CRACKS IN STEEL BY MEANS OF SUPERSONIC WAVES.

By C. H. DESCH, F.R.S., D. O. SPROULE, M.Sc., F.Inst.P., and W. J. DAWSON, A.Met.

(Figs. 7 to 35 = Plates XXI. to XXX.)

Paper No. 17/1946 *of the Alloy Steels Research Committee* (*submitted by the Hair-Line Crack Sub-Committee*).

Synopsis.

Section 1 *reviews previous methods of detecting flaws in steel by means of sound waves, especially of high frequency. A short account of a method of measuring damping of oscillations of high frequency and very small amplitude is included.*

Section 2 *describes apparatus employing piezo-electric quartz transmitters for producing intermittent pulses of supersonic waves and receiving them on similar quartz crystals after reflection, the reflected waves being electrically amplified and indicated on a cathode-ray oscilloscope. The conditions for obtaining sharp indications are discussed, as well as the effects of the degree of finish of the metallic surfaces under examination.*

In Section 3 *are given the results of applying the new method in works practice, including large masses, billets, plates, castings, and welds. The conditions necessary for the satisfactory use of the apparatus for practical testing are discussed. It is maintained that supersonic testing should be regarded primarily as a new instrument of investigation, giving information which cannot at present be obtained by more usual methods.*

Section 1.—Introductory.*

By C. H. DESCH, F.R.S. (Whitehead Iron and Steel Co., Ltd., Newport, Mon.).

Sound waves have long been used as a simple means of detecting flaws in steel, a familiar example being the tapping of railway wheels with a light hammer. The ringing note given out by a sound mass of steel becomes dull or harsh when a crack is present, and the unpleasant sound of a cracked bell is proverbial. Such a crude method serves only to detect gross flaws, as sound waves, being large in comparison with most of the defects likely to occur in practice, find their way round the obstacle. Various attempts have been made to make the test more sensitive, including the use of a stethoscope, but tests at the National Physical Laboratory showed the method to be entirely untrustworthy.

So-called acoustic methods of testing have therefore little importance, but by shortening the wavelength until it is comparable with the dimensions of the flaws to be expected an entirely new range of sensitiveness is reached. These short waves are known as "supersonic" or "ultrasonic" waves, the former term being preferable. As produced by modern methods their wavelengths in air range from 1·6 cm. to $0{\cdot}6 \times 10^{-6}$ cm., as compared with 130 cm. for the middle C of the piano. The velocity of sound in steel being nearly 16 times as great as in air, the wavelengths become :

At 20,000/sec., 25·1 mm.
At 5×10^{8}/sec., 0·01 mm.

Wavelengths between these values are generally used.

There are two principal methods of producing supersonic waves, depending on magnetostriction and on the piezo-electric effect respectively. In both methods advantage is taken of the fact that when an alternating potential is applied to a mass of suitable material an expansion takes place during one-half of the wave and a contraction during the other. A magnetostriction oscillator is of nickel or a nickel alloy, whilst a piezo-electric oscillator is of quartz or less often of tourmaline. The exciting circuit, tuned to the natural frequency of the oscillator, is provided by a thermionic valve. For high frequencies one of the harmonics is used instead of the fundamental oscillation.

The first application of supersonic waves to the detection of flaws in metals appears to have been in a German patent of 1931.[1] It was worked out in detail and applied to masses of steel up to

* Received February 19, 1946.

1 m. thick by Sokoloff.[2] The oscillator, built up of a number of pieces of quartz, was placed between two horizontal plane steel plates, the upper plate being in contact with the surface of the steel to be tested or, if that were not perfectly plane, with an intervening layer of mercury. The two steel plates were connected to the terminals of the circuit. A small flat-bottomed trough containing a liquid was placed on the top of the specimen, and a parallel beam of light reflected from its surface showed characteristic interference patterns produced by the waves, which could be projected on to a screen. Obviously such a method could give only very general indications.

An improvement consisted in producing a shadow picture of the defect.[3] The specimen was placed vertically and the beam of waves sent through horizontally, being received in a trough containing xylene in which aluminium flakes were suspended. These flakes set themselves perpendicularly to the direction of the train of waves. An internal flaw in the mass of metal deflects the beam and produces a dark shadow in the glistening suspension of aluminium. When the possibility of using supersonic methods of testing was brought to the knowledge of the Hair-Line Crack Sub-Committee in November 1939 it was this method which was selected for experiment. A somewhat similar apparatus was used to examine the quality of joints in girders, &c., contact being made through water, and the same apparatus was used to detect laminations in sheets.[4]

Much work in this field has been done in Russia, and as the original papers are rather inaccessible reference may be made to a review of the Russian literature.[5] In one form of the apparatus a telephone receiver was used to receive the transmitted waves for thicknesses of 8–10 cm. and a valve voltmeter for thicknesses up to 30 cm. Frequencies up to 10^7 cycles were employed and only 20–50 W. were required. The objects to be tested were immersed in oil, and in this form the apparatus, which was rather complicated, was used to detect flaws in Duralumin propeller blades and the heads of rails. A photographic record of the indications could be obtained.

Messrs. Henry Hughes and Son, Ltd., having much experience with supersonic apparatus, were approached by the author on behalf of the Hair-Line Crack Sub-Committee in April 1940, the shadow method of Pohlman being first considered. Experiment by this method failed to detect hair-line cracks, although gross discontinuities such as saw-cuts could be detected, and it was only in 1942 that Mr. D. O. Sproule, using the principle of echo-sounding, devised the method which is described in Section 2 of this paper. The power required is much less than that consumed in the Pohlman apparatus. As a consequence of discussions in the Sub-Committee, supersonic testing sets have been supplied by Messrs. Hughes to a number of steelworks and laboratories, and practical experiences in the testing of a variety of products are described in Section 3 of the paper.

The first demonstration of the apparatus to members of the Sub-Committee was on July 19, 1943, since when there has been constant collaboration between the makers of the instrument, the steelmaking firms, and the Sub-Committee.

In the meantime, experiments had been in progress in America, the results of which became known in this country only after the events described above. They may be briefly mentioned here. The Supersonic Reflectoscope, developed by Sperry Products, Inc., makes use of only a single quartz crystal, which both sends and receives the waves, which are sent out in pulses. An oscillograph is used as in the British instrument. The apparatus was devised particularly for use on interior surfaces, and the quartz crystal was sometimes ground to shape to fit the interior of a tube, contact being made with a film of oil.[6] For such purposes flexible leads up to 20 ft. long have been used with some sacrifice of sensitiveness, provided that the grain-size of the metal under test is small. With a frequency of 5×10^6 cycles/sec., each pulse consisting of only 5 waves, a $\frac{1}{2}$-in. brass plate with an average grain-size of 0·03 mm. gave twelve successive reflections in one experiment, with grains 0·075 mm. only six and with 0·105 mm. only three.

The Sonigage,[7] devised for the inspection of hollow propeller blades, does not measure the interval between emission and reception directly, but measures the frequency at which resonance is set up.

Some of the methods mentioned in the early part of this introduction made use of lenses to concentrate the supersonic waves, consisting of copper lens-shaped containers holding a liquid. The absorption was considerable, and it has been pointed out [8] that synthetic resin is preferable to copper. Experiments are being made with lithium, which should transmit 95·9% of the beam when immersed in paraffin. Spherical mirrors have been used in place of lenses.

In the earlier period of this investigation, methods depending on the measurement of the damping of acoustic waves were also considered. Most damping methods give rather unsatisfactory results on account of the very great absorption of energy in the appliances for holding the specimen, this often exceeding the absorption to be measured. The arrangement devised by the late Dr. Frommer [9] avoided this difficulty. Torsional oscillations were found to give results which were virtually independent of the fre-

quency and amplitude, whilst the methods of suspension were such as to make the absorption of energy in the supports entirely negligible. The source of power was an audio-frequency oscillator, in which two radio-frequency oscillators were arranged to give beats with a smoothly adjustable frequency of from 60 to 6000 cycles/sec. A power amplifier with an output of 12 W. feeds the exciting unit. The pole tips of a polarized electromagnet are placed close to a small block of low-hysteresis alloy cemented to the end face of the cylindrical specimen. There is an identical arrangement at the further end to act as receiver. This is connected to a four-stage amplifier. Amplitudes of vibration are indicated by a copper oxide rectifier voltmeter and a cathode-ray oscilloscope is connected across the amplifier to indicate the wave-form and to check the agreement of the vibration frequency of the specimen with the driving frequency. Measurements are made at all the torsional tones within the range of the apparatus. After setting the oscillator to the resonance frequency of the specimen the fine tuning control is adjusted until the amplitude is a maximum. The power is then shut off and the time taken for the amplitude to fall to half its initial value is taken with a stop-watch.

It was found that if two specimens in exactly the same state as regards composition and heat-treatment were compared, one containing internal hair-line cracks and the other being free from them, the damping of the cracked was higher than that of the uncracked specimen, but the method proved to be exceedingly sensitive to differences of heat-treatment. This property may prove to be useful. The condition of the surface of the specimen greatly influences the damping, the maximum torsional stress occurring in the surface. Means have therefore to be taken to remove rust and scale and to obtain a uniform surface.

With these precautions the method was found to give perfectly reproducible results. The difference in damping between the quenched and the tempered conditions of a steel with 0·6% of carbon was easily measurable and the same figures were obtained on repeating the cycle of heat-treatment. The torsional-oscillation method has the advantage over other means of applying the stress that it is independent of the frequency over a very wide range, and that it can be carried to a range of stress approaching that of the older methods of measuring damping, all of which suffer from the fact that some plastic deformation is always involved. Frommer's method allows of measurements well within the elastic range of the steel.

Although this method does not seem to be of general application in the detection of internal defects in steel on account of its sensitiveness to variations in the structural condition, it may prove a valuable means of investigating the changes brought about by heat-treatment. It has already been applied with success to the examination of light alloys, in which the structure is less dependent on thermal treatment than is that of steel, so that the presence of internal defects is shown up without ambiguity.

REFERENCES.

1. O. Muhlhausen: D.R.P. 569,598, 1931.
2. S. Sokoloff: *Technical Physics of the U.S.S.R.*, 1935, vol. 2, p. 522; *Physikalische Zeitschrift*, 1935, vol. 36, p. 142.
3. R. Pohlman: *Zeitschrift für Physik*, 1939, vol. 113, p. 697. British Patent 494,613, 1938.
4. A. Trost: *Zeitschrift des Vereins deutscher Ingenieure*, 1943, vol. 87, p. 352; *Sheet Metal Industries*, 1944, vol. 19, p. 255.
5. A. Behr: *Metallurgia*, 1940, vol. 23, p. 7.
6. F. A. Firestone: *Metal Progress*, 1945, vol. 48, p. 505.
7. W. S. Erwin: *Steel*, 1945, vol. 116, No. 10, p. 131.
8. P. J. Ernst: *Journal of Scientific Instruments*, 1945, vol. 22, p. 238.
9. L. Frommer and A. Murray: *Journal of The Iron and Steel Institute*, 1945, No. I., p. 45 P.

Section 2.—The Supersonic Flaw Detector.*

By D. O. SPROULE, M.Sc., F.Inst.P. (Messrs. H. Hughes and Son, Ltd., London).

(Figs. 7 to 16 = Plates XXI. to XXIV.)

Part I.—Introduction.

§ 1. The use of supersonic waves for the non-destructive testing of materials has frequently been proposed since the discovery of convenient methods of initiating and detecting such waves. This possibility depends on the use of a frequency high enough and a wavelength short enough to secure rectilinear propagation of the supersonic radiation. This condition is reached when the obstacle is large in comparison with the wavelength and, in general, a detectable shadow is cast and detectable reflection occurs when the target has dimensions of the order of one wavelength or greater. Most known materials will transmit supersonic waves a few millimetres or less in

* Received February 5, 1946.

length over a useful range of distance. Obviously this opens up the prospect of detecting flaws in the interior of bodies opaque to light.

§ 2. The analogy with X-rays immediately springs to mind, and appears to have been the guiding idea in most of the work published hitherto. A continuous supersonic source has been used, and various detectors have been employed to reveal the shadow or echo. The analogy with X-rays breaks down, however, in a number of ways, and this accounts for the meagre success claimed for the above method.

§ 3. X-rays are not reflected or refracted appreciably from the boundary of a solid or liquid medium, whereas supersonic rays are generally reflected and refracted heavily. This simple difference is of great importance in the practical application of supersonic waves to the detection of flaws. For instance, suppose that we wish to scan a sheet of steel or other solid by placing it between a supersonic transmitter and receiver in a liquid bath. It will be necessary for the radiation to be incident normally on the sheet to some accuracy, as total reflection will take place between 10° and 15° for water, oil, mercury, and most useful liquids. Moreover, even at normal incidence the coefficient of reflection at the liquid–solid interface will be so high that the energy due to direct transmission from the transmitter to the receiver will be small in comparison with the energy which has suffered multiple reflections between the parallel surfaces of the sheet or between the surfaces of the sheet and the walls of the bath. As a result, a flaw which would otherwise be capable of casting an easily detectable shadow is completely obscured by these multiple reflections. The same difficulty is met with in attempting to detect an echo due to a flaw when using a continuous train of waves. This is discussed further in § 39.

§ 4. In the device to be described here, the difficulty of multiple reflections is overcome by using a pulsing system similar to that used in a ship's echo-sounder. A train of waves is sent out which is so short that it occupies a space less than the distance between the boundaries of the medium being investigated. Moreover, the transmitted and reflected wave trains are shown on a cathode-ray tube in such a way that they do not interfere, and it is possible to detect a very small echo even though it may be followed by reflections containing hundreds or thousands of times as much energy.

§ 5. This desirable effect is secured by employing a system in which the cathode-ray time base is first set in operation, and a very short time later a short transmission is sent out. The echo and subsequent reflections cause transverse deflections of the cathode-ray spot and the results are oscillograms of the sort shown in Fig. 8. The transmission-time mark on the left of the oscillograms is due to electromagnetic-induction effects accompanying transmission and picked up by the receiver amplifier.

§ 6. To secure this clarity of indication it is essential to allow the successive echoes to die out before another transmission occurs (*see* § 39 and Fig. 16).

§ 7. The general appearance of the equipment is shown in Fig. 7.

Part II.—The Apparatus.

General Arrangement.

§ 8. Fig. 1 is a diagram of the various parts of the equipment. Raw A.C. is used to trigger the

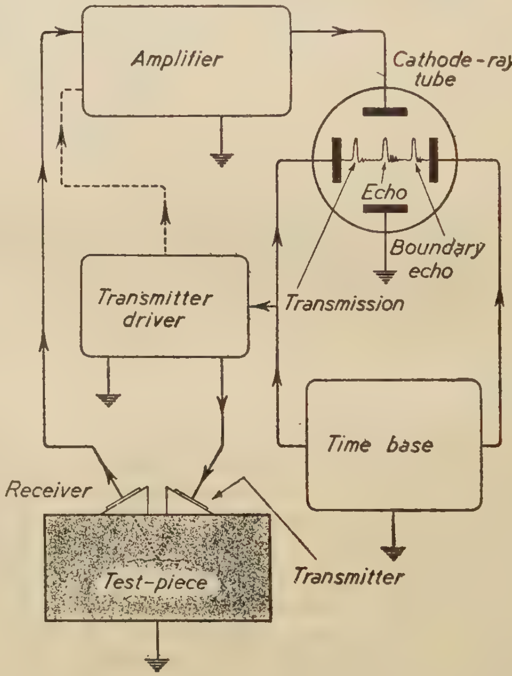


Fig. 1.—Schematic Diagram of the Apparatus.

thyratron time base once per cycle. The voltage impulse which sets the spot in motion across the screen is fed to the transmitter driver through a simple delay circuit to produce the transmission at an appropriate time. As shown in Fig. 1, the transmitter is mounted on a wedge which directs the beam of supersonic energy into the region of the specimen that is to be tested for flaws, and the receiver is tilted by a similar wedge to make it sensitive to reflected energy coming from the same region. This wedge system is shown in more detail in Fig. 2 (*b*), and a rough indication of the directional characteristic of the beam is shown in Fig. 3. In Fig. 3 (*a*) the transmitter and receiver are shown without wedges; in this position the system is insensitive to flaws near the surface, but beyond this it is capable of detecting flaws over a large range of distance.

§ 9. The receiver amplifier is arranged to give a vertical deflection to the spot at the moment of arrival of the echo; the time base is arranged to give an approximately uniform velocity of the spot from left to right.

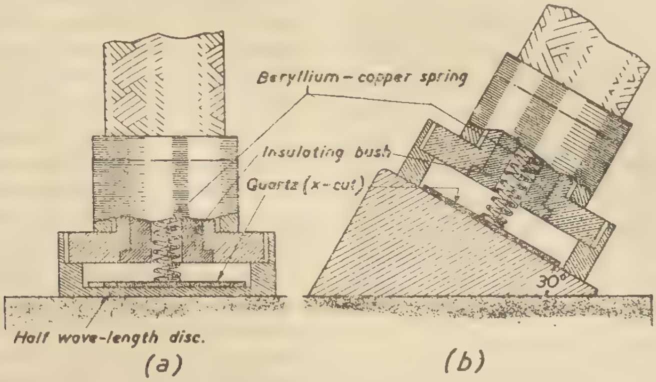


FIG. 2.—Probe Heads (a) without and (b) with wedge.

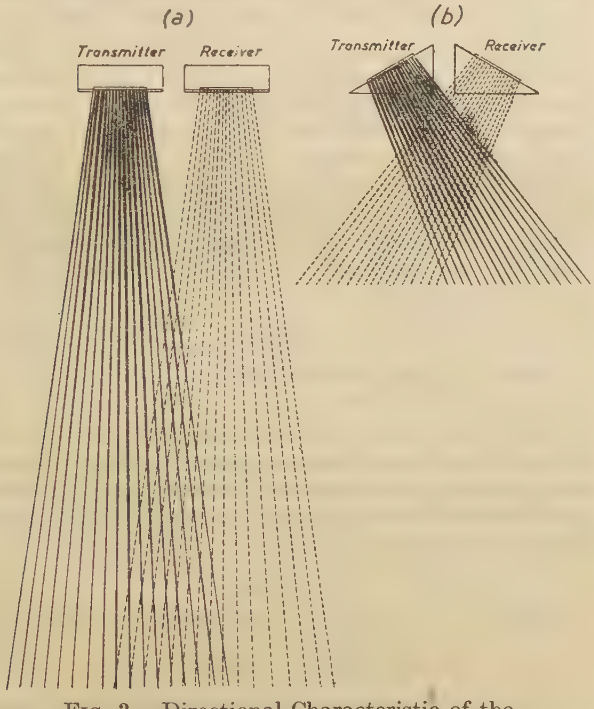


FIG. 3.—Directional Characteristic of the Transmitter–Receiver System.

The Transmitter–Receiver System.

§ 10. The piezo-electric effect of quartz is used to convert the energy of a damped train of electrical waves to a damped train of supersonic compressional waves. The returning echo is converted from a compressional-wave disturbance to an electrical vibration by the converse piezo-electric effect and is subsequently amplified. The transmitter and receiver are composed of similar crystals of quartz, each 2 cm. in dia. and approximately 0·1 cm. thick, with a natural frequency of $2\frac{1}{2}$ Mc./sec. In steel, aluminium, and most alloys of the latter, the total beam angle is about 16° and the wavelength is approximately 0·24 cm. Most metals have elastic constants which lie between these values and one-half of these values.

Both the transmitter and the receiver crystals are mounted in arrangements designed to give mechanical and electrical shielding which are commonly called "probes." These probes mainly take the two forms shown in Fig. 2. In Fig. 2 (*a*) the quartz is separated from the sample to be tested by a thin plate which may be only approximately 0·004 in. thick (non-resonant) or 0·050 in. thick (resonant). In Fig. 2 (*b*) the quartz is mounted on a metal wedge in order to incline the beam axis to the surface of the sample as shown in Fig. 3 (*b*). In special cases it may be desirable to use the bare quartz on the metal, as there is then only one oil film between the quartz and the sample to be tested.

The Transmitter Driver.

§ 11. The transmitter-driver unit applies a damped train of waves with an amplitude of about 300V. to the transmitter. The train is damped to half-value in about 4 cycles. The transmitter is connected in parallel with an inductance, and the damped train at a frequency of about $2\frac{1}{2}$ Mc./sec. is generated in this system by discharging a condenser through a thyratron. Alternative frequencies of $1\frac{1}{4}$ and $\frac{1}{2}$ Mc./sec. can be provided, as shown in Fig. 10.

The Receiver Amplifier.

§ 12. This is an inductance-compensated resistance-capacity coupled amplifier. Its total gain is in the neighbourhood of 100,000 times. Since the final stage is a pulse amplifier, the frequency

response of the first four stages only is shown in Fig. 4.

The Time Base.

§ 13. The time base is a very simple one which involves the discharge of a condenser through an inductance by means of a thyratron. The thyratron conducts current only during the working stroke and is then extinguished and the condenser recharges through a resistance. To a first approximation the voltage output from this arrangement is half a sine-wave, this being the half between the peak and the trough which is straight enough for a sufficient length of time to be useful in this case. The time-base velocity is changed by varying the

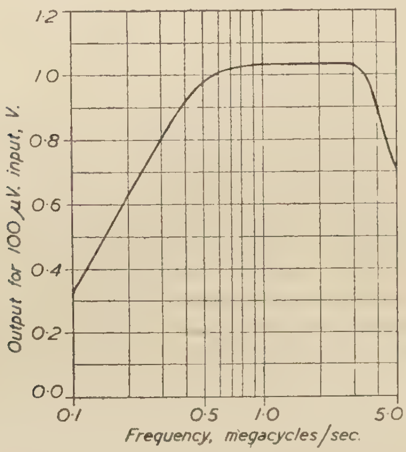


Fig. 4.—Frequency Response of Amplifier, showing first four stages.

inductance. In the extreme cases the working stroke may occupy as little as 20 μ sec. or as much as 3000 μ sec., whereas the return stroke and waiting time is nearly 20,000 μ sec. Because of the long waiting time it is necessary to arrange that the beam is visible only during the working stroke and is completely extinguished during the return stroke. A portion of the working-stroke voltage is applied to the control grid in conjunction with the voltage-limiting diode in order to secure a brightening impulse which increases the intensity of the spot by the required amount during the working stroke only.

Part III.—Some Theoretical Considerations of Practical Importance.

§ 14. The flaw detector is an application of echo-sounder principles to sounding in a "solid sea." As the probes are moved about the surface of the medium the echoes vary in time of arrival and in intensity. Most of these variations have some significance, and in order to derive the full benefit from them it is necessary to know something of the physical laws which govern the behaviour of the sound as it travels out from the transmitter, through the coupling medium to the sample, back from the flaw or from the boundary of the medium under investigation, and finally back into the receiver as an echo. No attempt will be made here to derive these laws from the fundamental laws of mechanics, but some useful equations will be given and their relevance to flaw detection will be indicated. The actual user who requires more complete information is referred to standard text-books on sound and supersonics.*

§ 15. In using the supersonic flaw detector it must be constantly borne in mind that both the transmitter and the receiver are directional. The complete and precise description of the directional characteristic at all distances from the quartz is very elaborate and is not necessary for most purposes of the flaw detector. The main point to bear in mind is that most of the energy streams away from the quartz in the form of a conical beam, with the axis of the beam lying along a line normal to the centre of the quartz. The exact distribution of energy in the beam depends upon various factors in practice and, in the ideal case, upon the ratio of the radius of the disc to a wave-length. In the ideal case a plane circular area of a homogeneous medium is set into motion in such a way that the amplitude and phase are equal over its whole surface. For positions remote from this surface, the beam has a maximum intensity on the axis, and falls off to a minimum at an angle θ derived as follows:

$$\theta = 0{\cdot}61 \sin^{-1} \lambda/r. \quad . \quad . \quad . \quad (1)$$

where λ = wavelength, and
r = radius.

§ 16. There are several precautions to be observed in using this equation. The radius r can generally be measured direct from the disc, and in most cases λ is most conveniently obtained from the equation:

$$\lambda = C/n \quad . \quad . \quad . \quad . \quad . \quad (2)$$

where C = velocity in the medium in which the beam exists, and
n = frequency of vibration.

§ 17. Some caution must be employed in taking the value for C from tables. In most cases tables showing the velocity for liquids can be used without fear of error, but, in the case of solids, it should be remembered that vibrations travel at different speeds in the same solid under different conditions. In most applications of the flaw detector so far, we have been concerned mainly with the longitudinal form of vibration in the bulk of a solid. This travels with the highest velocity

* A. B. Wood, "Text-Book of Sound." London: G. Bell and Sons, Ltd. L. Bergmann, "Ultrasonics." London, 1938: G. Bell and Sons, Ltd.

and so the echo due to this type of vibration arrives first, and can be clearly recognized. The velocity is determined by the elastic constants of the solid and the density, according to the following equation :

$$C = [(k + \tfrac{4}{3}\mu)/\rho]^{\frac{1}{2}} = (1 - \sigma)E/(1 - \sigma - 2\sigma^2)\rho]^{\frac{1}{2}} \quad . \quad (3)$$

where k = volume elasticity,
μ = rigidity,
E = Young's modulus,
σ = Poisson's ratio, and
ρ = density.

§ 18. The transverse mode of vibration which can be seen in some of the oscillograms of Fig. 8 travels more slowly and is given by the equation :

$$C = (\mu/\rho)^{\frac{1}{2}} \quad . \quad . \quad . \quad . \quad . \quad (4)$$

§ 19. There are at least two types of surface wave which also travel more slowly and which sometimes appear as an interfering disturbance against which precautions must be taken. (*See* § 27.) Finally, in a bar which is much less than a wavelength in diameter, a longitudinal vibration has a velocity (V) less than the "bulk" velocity which is given by the equation :

$$V = \sqrt{E/\rho} \quad . \quad . \quad . \quad . \quad . \quad (5)$$

where E = Young's modulus, and
ρ = density.

§ 20. Practical considerations dictate that the transmitter and the receiver must be mobile, and it is therefore necessary to use a fluid coupling medium between the transmitter, the receiver, and the sample under test. To understand the possibilities and the limitations of this technique, one should be thoroughly familiar with two laws governing the transfer of wave motion from one medium to another. The first is the law governing the change in direction of travel of the wave front, *i.e.*, the refraction in passing from one medium to another; the second law is that governing the intensity in the reflected and the refracted energy.

§ 21. The angle of the refracted ray is given by the well-known sine law (Wood, *loc. cit.*, p. 301) :

$$\frac{\sin\theta_1}{\sin\theta_2} = \frac{C_1}{C_2} \quad . \quad . \quad . \quad . \quad . \quad (6)$$

where θ_1 = angle of incidence,
θ_2 = angle of refraction,
C_1 = velocity in first medium, and
C_2 = velocity in second medium.

In the case of water and steel, $C_1 = 1{\cdot}5 \times 10^5$ and $C_2 = 6{\cdot}1 \times 10^5$ cm./sec. For small angles, $\sin\theta_1 = \theta_1$ and $\sin\theta_2 = \theta_2$. In this case a small inclination of the surface of the solid to the wave front is magnified over four times.

§ 22. Total internal reflection occurs when $\theta_2 = 90°$:

$$\sin\theta_1 = \frac{C_1}{C_2}.$$

For the case of water and steel cited above $\theta_1 = 14°$, and for all angles greater than this no energy penetrates the solid.

§ 23. Wood (*loc. cit.*, p. 302) gives the ratio of amplitude in the reflected and the incident rays as :

$$R = \frac{\xi r}{\xi i} = \frac{R_1 - R_2}{R_1 + R_2} \quad . \quad . \quad . \quad (7)$$

where R_1 and R_2 are the products $\rho_1 C_1$ and $\rho_2 C_2$, respectively—products defined as the "specific acoustic resistances" of the media. In the case of water R_1 is $1{\cdot}5 \times 10^5$ and in the case of steel R_2 is $4{\cdot}75 \times 10^6$. Substituting these values in the above equation :

$$R = \frac{46 \times 10^5}{49 \times 10^5} = 0{\cdot}94.$$

§ 24. The energy is proportional to the square of the amplitude so long as the wave motion is in the same medium, so that the ratio of reflected to incident energy is given by $(0{\cdot}94)^2 = 0{\cdot}88$. Thus 89% of the energy is reflected and only 11% is transmitted. Expressed as a voltage amplitude developed in the receiver and taking the incident energy as giving unit deflection, the reflected ray will give a deflection of 0·94 and the transmitted energy a deflection of 0·33. In order to detect the echo the transmitted energy must return through the boundary and is then reduced to 0·11 of the deflection due to the incident energy. This is quite apart from attenuation due to the divergence of the beam or attenuation on reflection from the target producing the echo.

§ 25. It is clear that when the beam is projected from a liquid into a solid the echo is considerably weaker owing to the passage from one medium to another. Moreover, it must be detected in the presence of a very much greater interfering signal due to undesired echoes from the surface of the solid. Fortunately we are not forced to work under these conditions and we can secure the transfer of energy in the transmitter system to the sample under test by using a very thin film of liquid. In this case the following expression must be used instead of equation (6) :

$$\frac{\text{Reflected energy}}{\text{Incident energy}} = \left(\frac{\xi r}{\xi i}\right)^2$$
$$= \left(\frac{R_1}{R_2} - \frac{R_2}{R_1}\right)^2 \Big/ \left\{4\cot^2\frac{2\pi l}{\lambda} + \left(\frac{R_1}{R_2} + \frac{R_2}{R_1}\right)^2\right\} \quad . \quad (8)$$

This is based on Wood's equation (10) (*loc. cit.*, p. 306). Using a value for R_1 of $1{\cdot}5 \times 10^5$, and for R_2 of $4{\cdot}75 \times 10^6$ (for steel), a curve has been calculated and is shown in Fig. 5 over a range of values of l/λ from 0 to 0·25. The curve from 0·25 to 0·5 is a mirror image of the curve shown and the curve from 0·5 to 0·75 repeats the first $\frac{1}{4}$-wavelength, and so on, to infinity, if absorption is neglected. This curve is very interesting from

the point of view of application. It shows that the energy in a reflected beam is one-half that of the incident beam for a ratio of l/λ of 0·01. As the wavelength in water is only 0·06 cm., the thickness of film which is capable of reflecting half the energy is only 0·0006 cm., or 0·00025 in.

§ 26. It is implicit in the development of the equations which govern the transfer of energy from solids to liquids that there must be continuous molecular contact, *i.e.*, the liquid must wet the surface of the solid. Oil is a suitable liquid for most purposes. Soapy water, liquid soap, mercury, mercury amalgams, and many other liquids have been used on occasion. Plain water on an oily metal surface would appear to be unsuitable. Mercury and its amalgams must be avoided in the case of aluminium and its alloys as air reacts rapidly on the aluminium in the amalgam which readily forms when mercury touches aluminium.

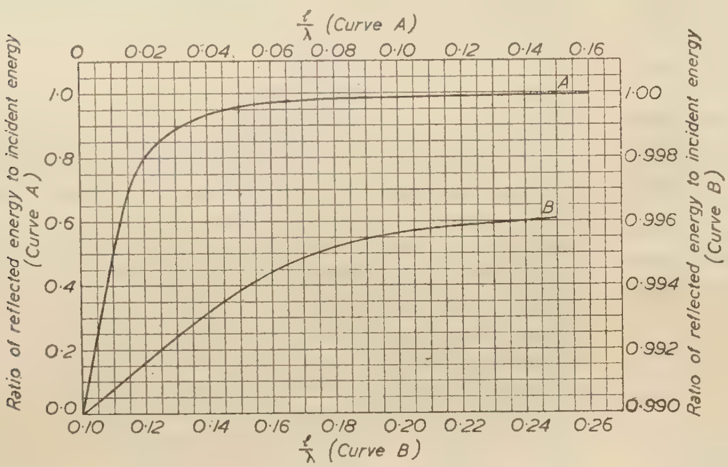


FIG. 5.—Transmission through Thin Plates. *A* is the complete curve from 0 to 1·000, while *B* is a magnified portion from 0·990 to 1·000 for the ratio of reflected energy to incident energy.

§ 27. If the surface of a test-sample is milled, it is generally corrugated by the tool, and in this case the transmitter rests on a series of lines spaced at regular intervals. This gives rise to a diffraction grating effect if the interval between the lines is half a wavelength or more. The velocity of the surface wave is lower than the velocity of the compressional wave in the bulk of the material and it happens that the interval between lines more often compares with the wavelength for this wave than for the compressional wave. In particular, if the interval between the corrugations corresponds to a wavelength for the surface wave, the transmitter will send a lot of energy along the surface and the same condition will cause the receiver to be sensitive to that energy and, as a result, a disturbance may be noted if the transmitter and receiver are placed with their centres on a line perpendicular to the corrugations. It will readily be seen that if the transmitter and receiver are placed with their centres on a line parallel to the corrugations, then reinforcement will not take place, and the sometimes troublesome " cross noise " will not appear on the screen and will not confuse the interpretation of results. This is shown in Fig. 12.

Use of the Beam.

§ 28. With the above theoretical points in mind we may now turn to the problem of making the best use of the beam. It has been shown why it is preferable to apply the transmitter and receiver to the surface of the sample to be tested instead of shooting a beam of supersonics at the solid sample through a liquid. For the time being let it be assumed that the sample has a plane surface and that the corrugations are small compared with the $\frac{1}{4}$-wavelength and may therefore be treated as a plane surface. Further, let it be assumed that we have placed the probes on the sample with their axes parallel, as shown in Fig. 3 (*a*), and the beams intercepting at a distance of about 4 in. Under most conditions of use there is a boundary echo which is very often referred to as the bottom echo. If another echo appears earlier than the boundary echo it is sufficient to show that there is a flaw in the material. The detection of an echo from a single position on the material does not usually permit the flaw to be located at all accurately. If the secondary beams are included in our reckoning the degree of ambiguity as to the position of the flaws is considerable. The only fact conveyed by the position of the echo is the time of " go " and " return " of the sound energy and this merely serves to place the target on a parabola, and because of the existence of secondary beams the parabola may subtend quite a large area at the transmitter–receiver position. If the flaws are small, the echo will generally be traced to a flaw inside the primary beam.

§ 29. Since it is known that the maximum intensity in the beam lies along a line perpendicular to the centre of the transmitter and also that the receiver sensitivity is a maximum along a line perpendicular to the centre of the receiver, it is possible to locate the target more accurately by adjusting the transmitter–receiver system to give the maximum response. It is clear from Fig. 3 that the results for targets close to the surface can be improved by tilting the transmitter and receiver. In this case the position of the target can also be more closely defined by

shifting first the transmitter and then the receiver to give the optimum result, and it will be appreciated that the position of the target can be checked by two methods, one depending on the range shown on the cathode-ray oscillograph, and the other depending on the intersection of the transmitter–receiver axes. Using this latter system, flaws can be detected within $\frac{1}{2}$ in. of the surface, as shown in the oscillogram of Fig. 11. Generally speaking, the flaw can be located to an accuracy of about $\frac{1}{4}$ in. up to distances of 1–2 ft.

Reflection and Scattering from Various Targets.

§ 30. As most of the targets in practice are very irregular in shape, making it impossible to calculate the reflectivity, no detailed quantitative analysis will be given here. The main physical considerations which must be borne in mind in interpretation relate to certain idealized cases such as reflection from a plane surface, a disc, a sphere, and a rough or mat surface. To simplify the discussion it will be assumed that the surface in question is backed by air, and in the majority of cases this assumption is a sufficiently close approximation for practical purposes, as a void in the interior of a solid body, even when as thin as a wavelength of light, is still capable of giving a very powerful reflection.

§ 31. A plane surface which is a large number of wavelengths in extent will give specular reflection of the beam, and if the transmitter, receiver, and flat reflecting surface are suitably oriented, an intensity of reflection will be obtained corresponding to that obtained with the transmitter and receiver facing one another, for the same distance of travel of sound. According to the usual convention, a reflecting surface is taken as flat if the deviations from a true plane are nowhere greater than $\frac{1}{20}$-wavelength. The same criterion holds for regularly curved surfaces. To produce a mat surface the irregularities must amount to $\frac{1}{4}$-wavelength or more.

§ 32. A reflecting disc placed with its plane perpendicular to the distance of travel of the wave will reflect its energy according to equation (1) § 15. If the disc is more than a few wavelengths in diameter, something like specular reflection will be obtained. For instance, it is generally noted that hair-line cracks will give detectable echoes only when they are approximately parallel to the surface from which detection is attempted.

§ 33. Reflection from a cylindrical cavity in the interior of a solid is of some practical importance. For a cylinder of large radius and relatively close to the transmitter–receiver system, the reflectivity approaches that for a plane surface. A long thin cylinder placed many diameters from the transmitter–receiver system becomes a " line scatterer " as its diameter approaches and becomes less than a wavelength. In this case the reflection is specular in a plane containing the axis of the cylinder, but is omnidirectional in a plane perpendicular to the axis of the cylinder. (*See* § 37 and Fig. 9).

§ 34. A sphere is the only target for which it is unnecessary to take into account its orientation with regard to the transmitted beam and the position of the receiver; the reasons are obvious. At one extreme, reflection from a sphere of large radius approaches reflection from a plane surface, and at the other extreme the echo can be treated as scattering from a body that is small in comparison with the wavelength. As Rayleigh has shown, in this latter case, the amplitude of the scattering varies directly as the volume of the scatterer and inversely as the square of the wavelength of the incident sound. Thus, by increasing the wavelength by a factor of four, the amplitude of the reflected sound from porosity can be decreased sixteen times, which is, of course, a very great practical advantage. The frequency employed will naturally depend on whether it is desired to detect the porosity or to detect a major flaw in the presence of porosity.

Part IV.—Some Typical Results.

§ 35. In Section 3 of this paper, a detailed discussion is given covering problems of practical application. It is intended here to present only a few results obtained with the flaw detector, mainly relating to cases where the physical conditions are known and have a special significance, or which will aid in understanding the results obtained in practice.

§ 36. Fig. 8 (*a*) shows the arrangement of probes on wedges as used to detect a series of drilled holes ranging from $\frac{1}{32}$ to $\frac{1}{4}$ in. in dia., drilled parallel to the surface from which they were detected and $1\frac{1}{4}$ in. from it. Fig. 8 (*b*) shows the oscillograms so obtained. The disturbance to the left of the oscillograms marks the moment of transmission. This is deliberately introduced in order to provide a zero time mark. The flaw echo is to the right of the centre of the trace, and the amplitude shown is with reduced amplifier gain in order to avoid overloading of the amplifier by the weaker echoes. Overloading does occur on the echoes from the $\frac{5}{64}$-, $\frac{1}{8}$-, and $\frac{1}{4}$-in. holes, which explains why the echoes from these targets change less than one would expect from the change in diameter. The boundary echo is shown on the extreme right.

§ 37. These oscillograms (in particular that of the $\frac{1}{32}$-in. dia. hole) should be compared with those shown in Fig. 9 (*b*). As indicated in Fig. 9 (*a*), the target is of about the same size and orientation with respect to the transmitter–receiver system, but about 20 times farther away. Hence, the

time base is slowed down accordingly. The echoes are so reduced in length that they are mere spikes. In the photograph they appear to be somewhat less conspicuous, but in practice this is not the case as the brilliance is greater at low speed, other factors being constant. Full gain was employed.

§ 38. Fig. 8 should also be compared with Fig. 13. In the latter case the target is perpendicular to the surface on which the probes are placed. Full amplifier gain was used, and, even so, the echo from the $\frac{1}{32}$-in. hole, at a distance of $1\frac{1}{4}$ in., is barely distinguishable.

§ 39. The oscillogram in Fig. 16 shows multiple echoes obtained using a steel plate $4\frac{1}{2}$ in. thick. It is possible to count 24 successive echoes and the amplitude is reduced to only one-third. The 24th echo has travelled some 18 ft., and this requires a time of about $\frac{1}{500}$ sec. It will be readily appreciated that if the repetition rate was as high as 500 cycles/sec. it would be impossible to distinguish a small echo in the presence of the persisting reverberation. A little consideration of this oscillogram would also show why continuous-wave methods have generally failed, as the reflected energy from a target will usually be superimposed on a much greater reverberation intensity.

§ 40. Fig. 14 (*a*) shows curved adaptors for use with a round bar. A simple method of making these adaptors is given in Section 3 of this paper. Fig. 14 (*b*) shows the echo obtained from the end of a $\frac{5}{8}$-in. dia. hole, 1 in. long, drilled radially in the far side of the bar from the probes.

§ 41. Fig. 19 is self explanatory. The time-base velocity was held constant and the inductance across the transmitting quartz was varied to give the frequencies shown.

§ 42. Fig. 15 (*a*) shows the arrangement used to investigate the effects of surface roughness with various coupling media and frequencies.

§ 43. Fig. 15 (*b*) shows the oscillograms obtained under the following conditions:

(1) Machined surface with oil ($2\frac{1}{4}$-Mc./sec. filter): Oscillograms (i)–(iii).

(2) Rough surface, as-rolled, with oil ($2\frac{1}{4}$-Mc./sec. filter): Oscillograms (iv) and (v).

(3) Rough surface with oil ($1\frac{1}{4}$-Mc./sec. filter): Oscillograms (vi) and (vii).

(4) Rough surface with amalgam ($2\frac{1}{4}$-Mc./sec. filter): Oscillograms (viii) and (ix).

Oscillogram (i) shows a bottom echo only, while oscillogram (ii) shows a small flaw which gives a good echo but at the same time does not obscure the bottom echo. The flaw shown in oscillogram (iii) is so large that the bottom echo is almost completely masked. Oscillogram (iv) shows the best bottom echo and oscillogram (v) the strongest flaw echo that could be obtained under conditions (2). Oscillograms (vi) and (vii) show the effect of a $1\frac{1}{4}$-Mc./sec. filter in conjunction with a rough surface and oil, and it will be seen that much stronger echoes were obtained in both cases. For an explanation of this difference *see* § 26. The use of a lower frequency reduces the effective thickness of the oil film between the wedges and the sample. The alternative method of reducing the effect of the coupling medium is to employ a medium which has physical properties more closely resembling those of the steel, and oscillograms (viii) and (ix) show the effect of using a rough surface and an amalgam. Reverting to the $2\frac{1}{4}$-Mc./sec. filter, it will be seen that the amalgam is much better than the oil. Instructions on the preparation of a suitable amalgam are given in Section 3 of this paper.

§ 44. Fig. 6 shows the surface contour of the rough surface of the rolled billet used to produce the oscillograms of Fig. 15 (*b*).

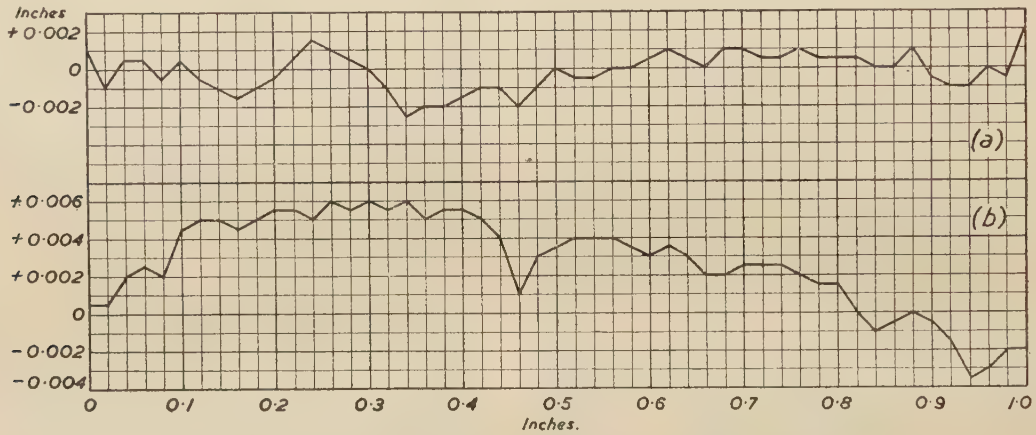


Fig. 6.—Contour of Rolled Billet along 1 in. of Surface (*a*) in the direction of rolling, and (*b*) transverse to the direction of rolling.

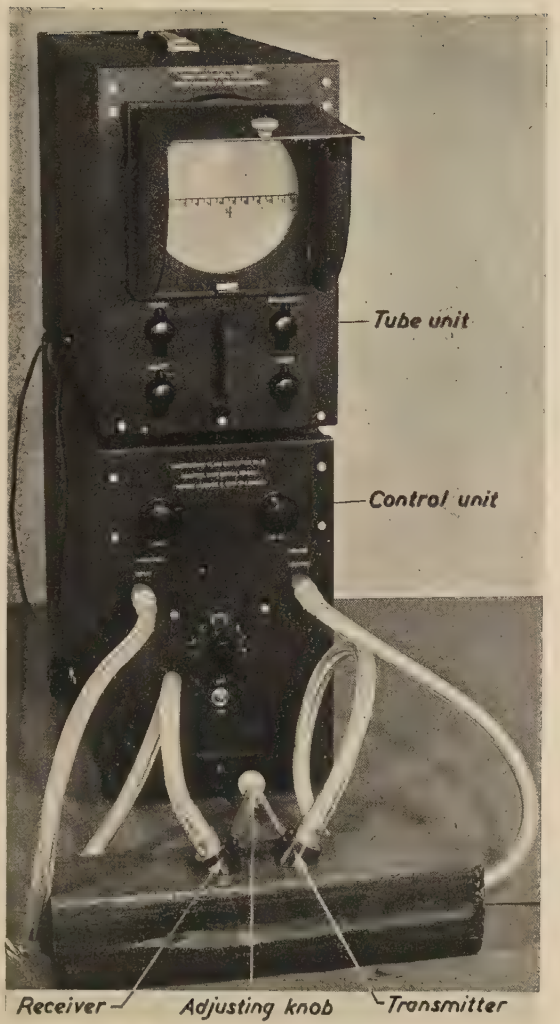


FIG. 7.—General Appearance of the Apparatus.

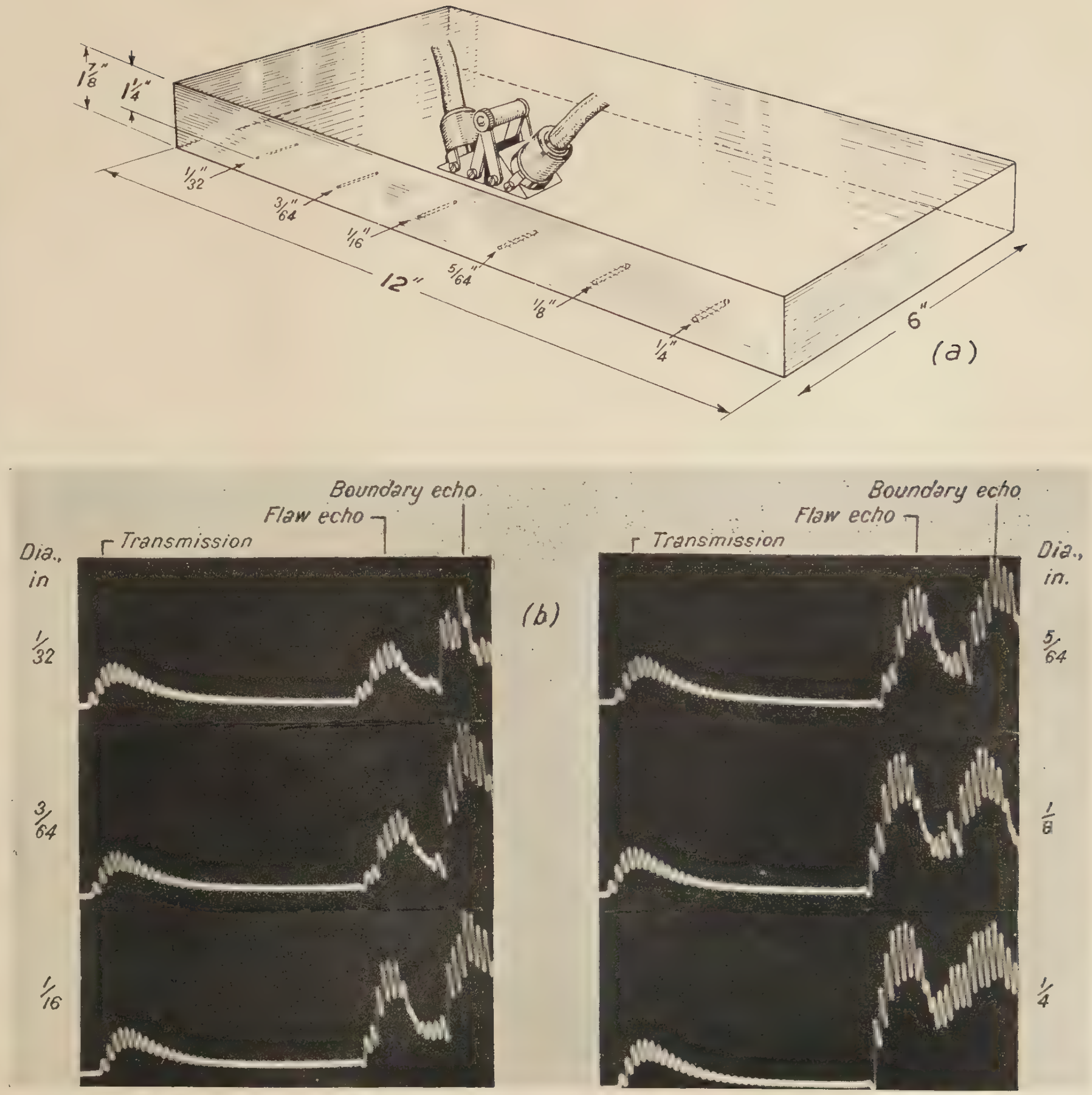
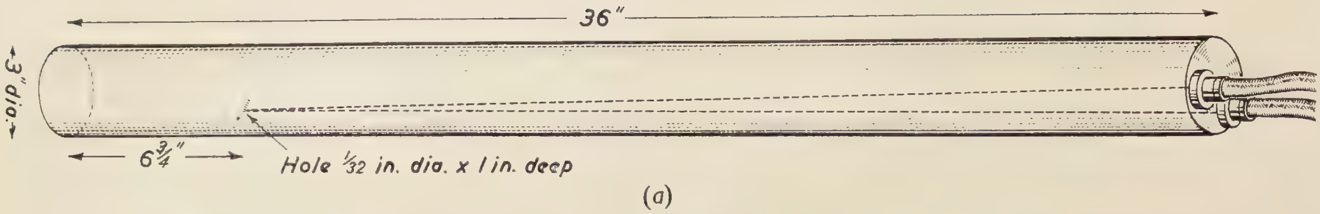


FIG. 8.—Investigation of the Reflections from Holes Drilled Parallel to the Surface, showing (*a*) the general arrangement, and (*b*) the oscillograms obtained.

[*Desch, Sproule, and Dawson.*
[*To face p.* 328 P.



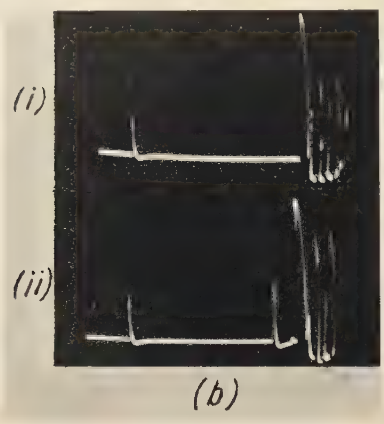


Fig. 9.—Detection of a Small Hole at a Large Distance, showing (*a*) the position of the hole, and (*b*) oscillograms obtained with (i) no hole, and (ii) the hole shown in (*a*).

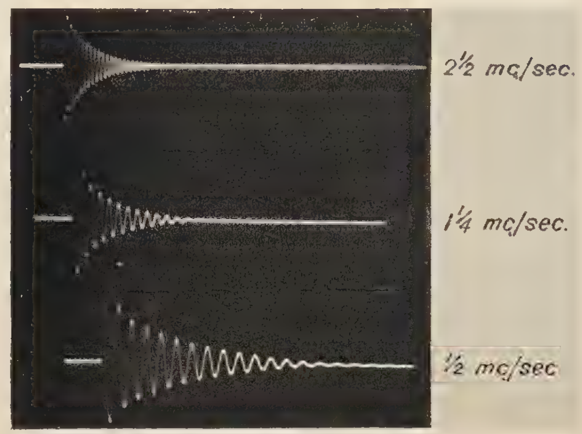


Fig. 10.—Voltage Wave Form Applied to Transmitter Obtained with Various Frequencies.

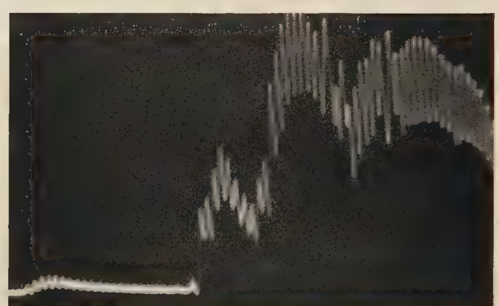
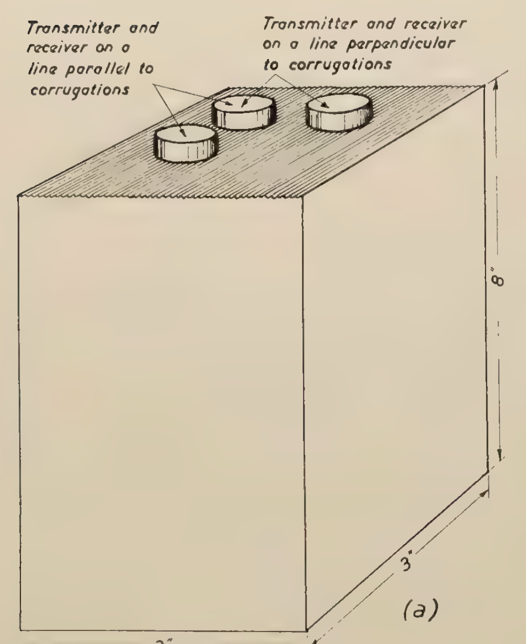


Fig. 11.—Oscillogram Showing Detection of Flaw at $\frac{7}{16}$ in. from Surface.



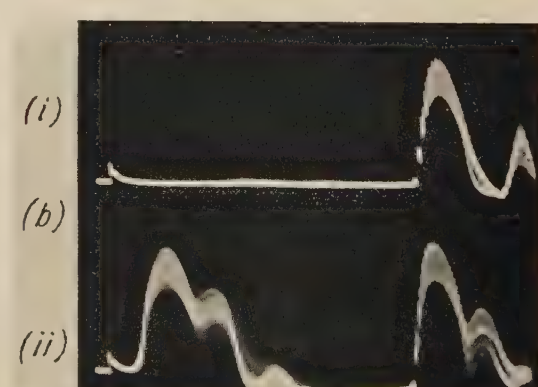
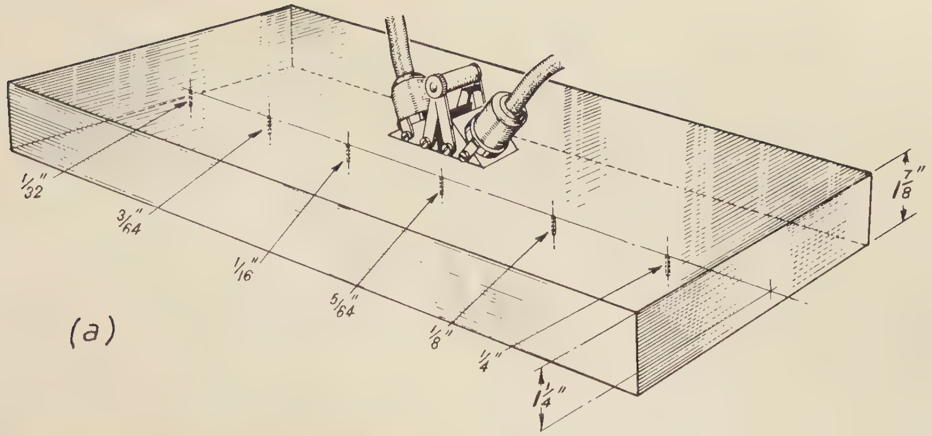


Fig. 12.—Investigation of the Effect of Regular Surface Corrugation, showing (*a*) the sample used and (*b*) oscillograms obtained with probes on a line (i) parallel and (ii) perpendicular to corrugations.

[*Desch, Sproule, and Dawson.*



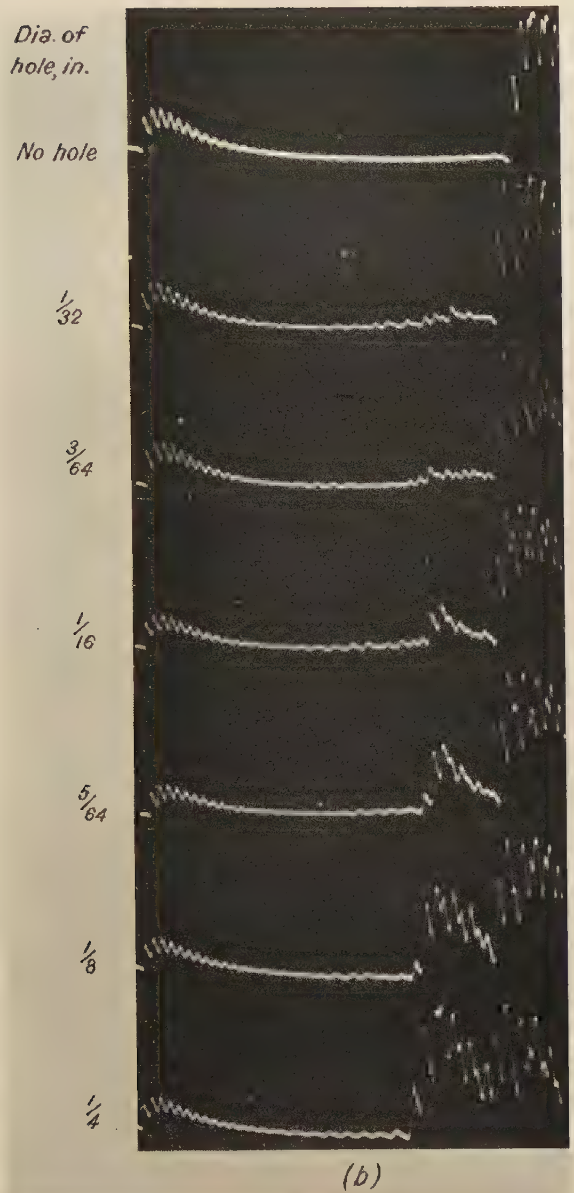
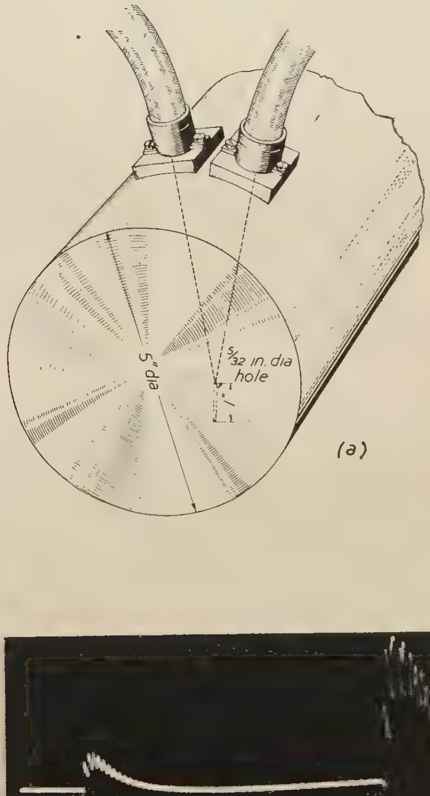


FIG. 13.—Investigation of the Reflections from Holes Drilled Perpendicular to the Surface, showing (*a*) the general arrangement, and (*b*) the oscillograms obtained.



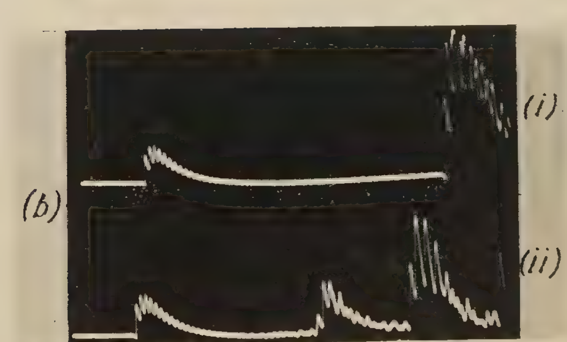


FIG. 14.—Investigation of the Reflections from a Hole Drilled in a Round Bar, showing (*a*) arrangement of the probes, and (*b*) oscillogram obtained with (i) no hole, and (ii) the hole shown in (*a*).

[*Desch, Sproule, and Dawson.*

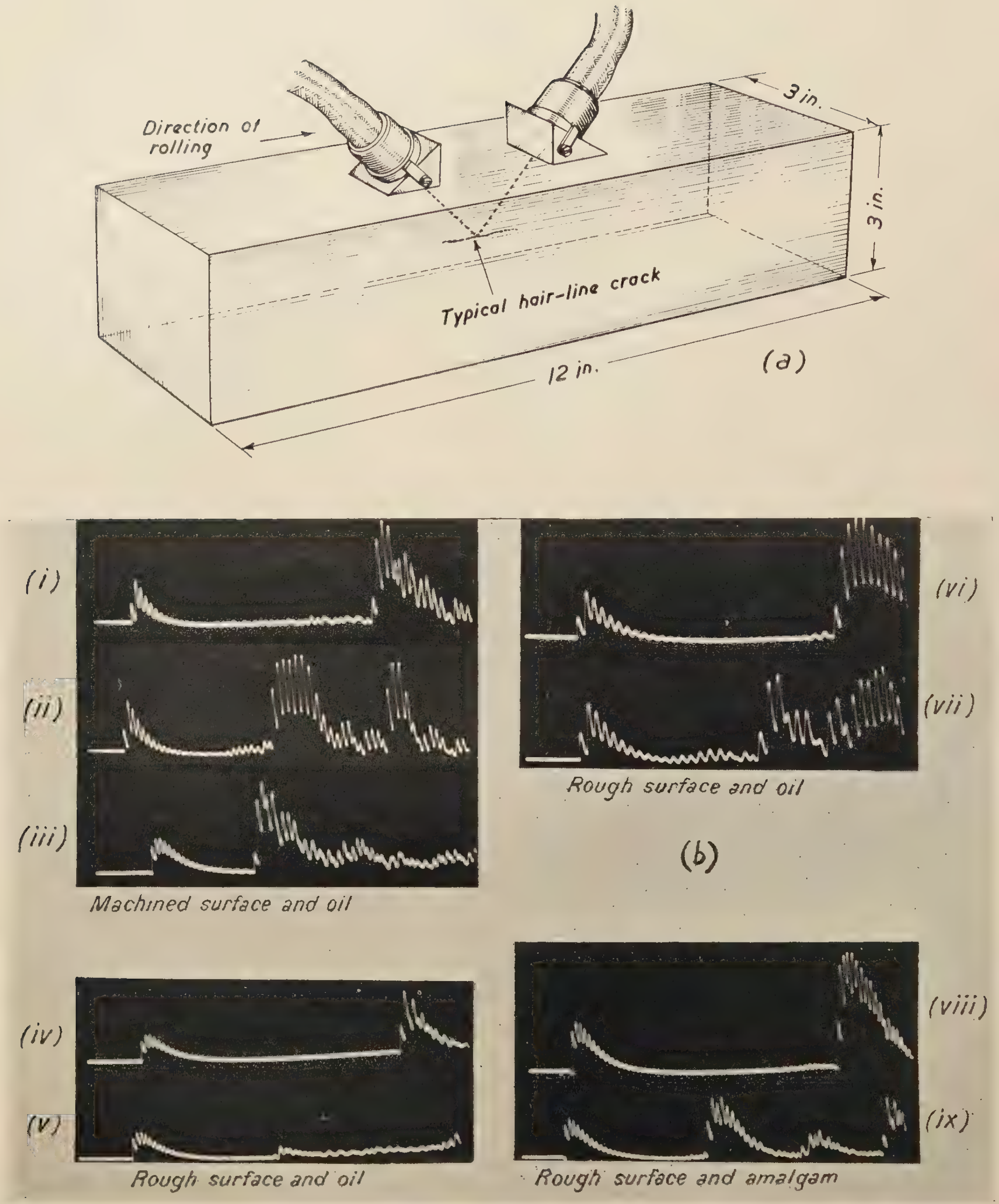


Fig. 15.—Investigation of Effects of Surface Condition, Coupling Media, and Frequency, showing (*a*) arrangement of probes, and (*b*) oscillograms obtained.

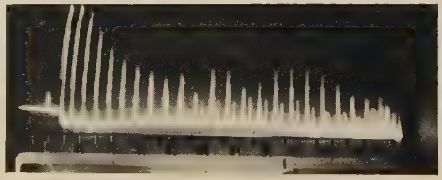


Fig. 16.—Multiple Echoes Obtained from a Steel Plate $4\frac{1}{2}$ in. Thick.

[*Desch, Sproule, and Dawson.*

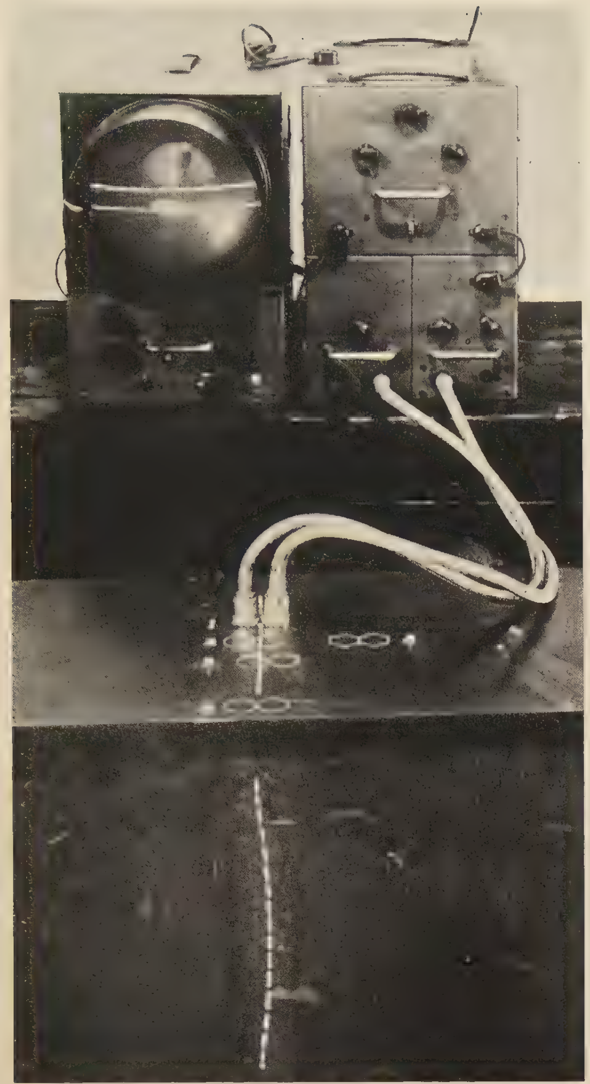


FIG. 17.—Method of Testing for an Internal Clink.

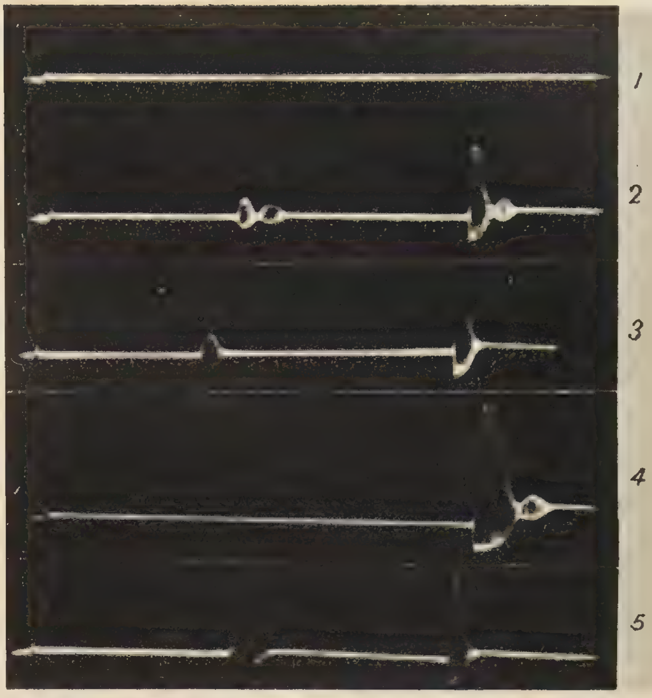


FIG. 18.—Results Obtained from Various Positions (indicated in Fig. 17) in the vicinity of the clink. Indications of hair-line cracks are visible within the central zone of the block.

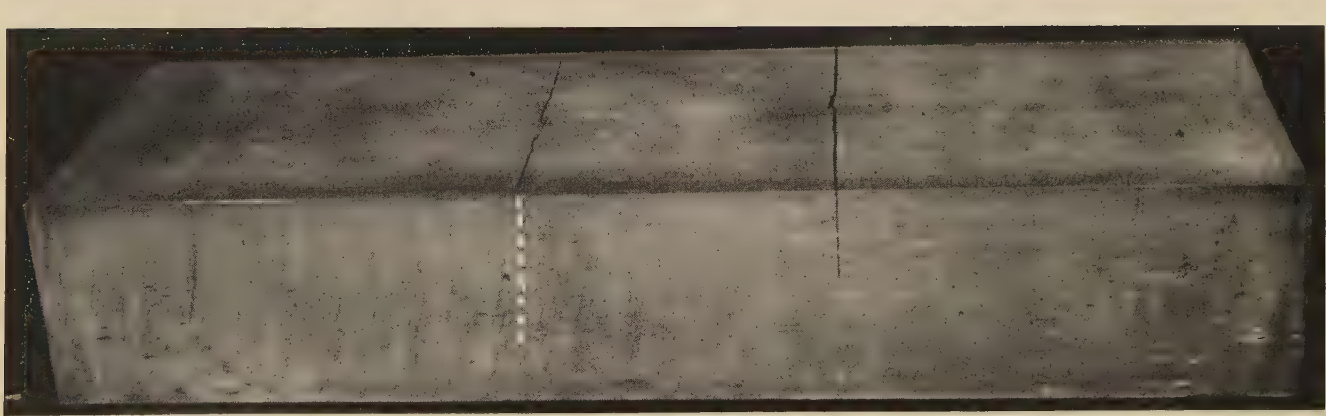


FIG. 19.—Coincidence in the Estimated and Actual Positions of the Clink, after half-sectioning.

[*Desch, Sproule, and Dawson.*

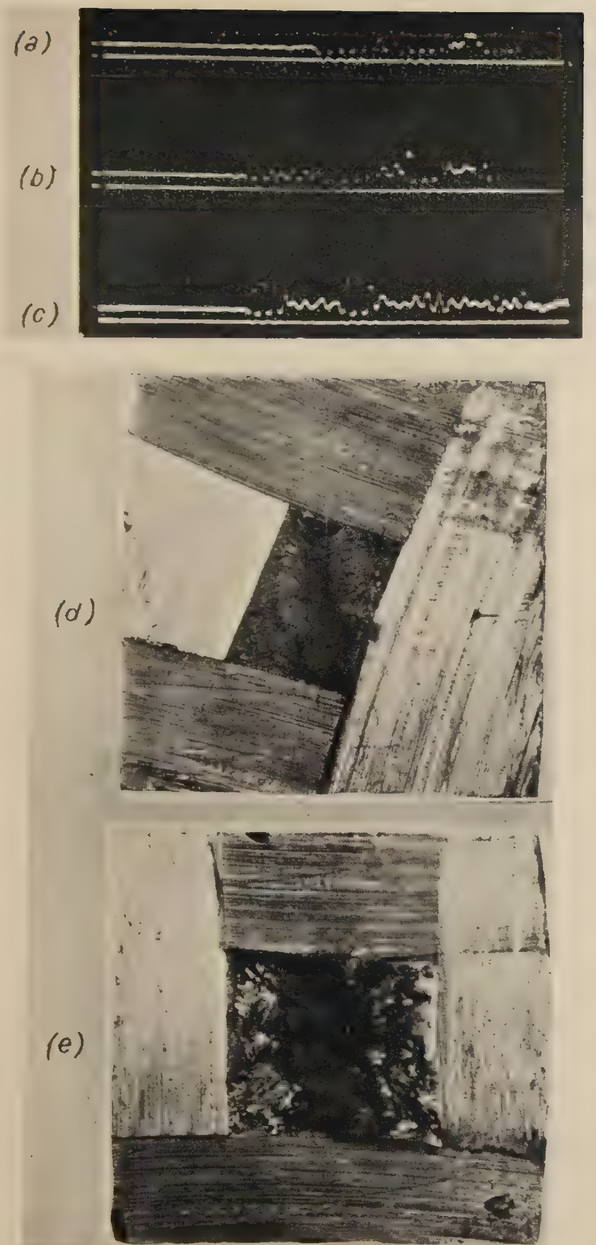


FIG. 20.—Detection of Pipe in High-Alloy Steel.
(a) Unpiped bar, no defects.
(b) Edge of piped bar, defects beginning to show.
(c) Centre of piped bar, defects well marked.
(d) Unpiped bar.
(e) Piped bar.

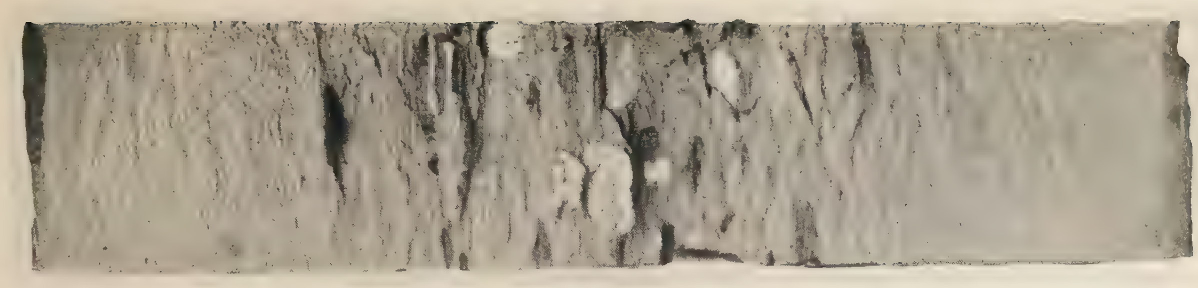


FIG. 21.—Fracture through Hair-Line Cracks. (Actual size.)

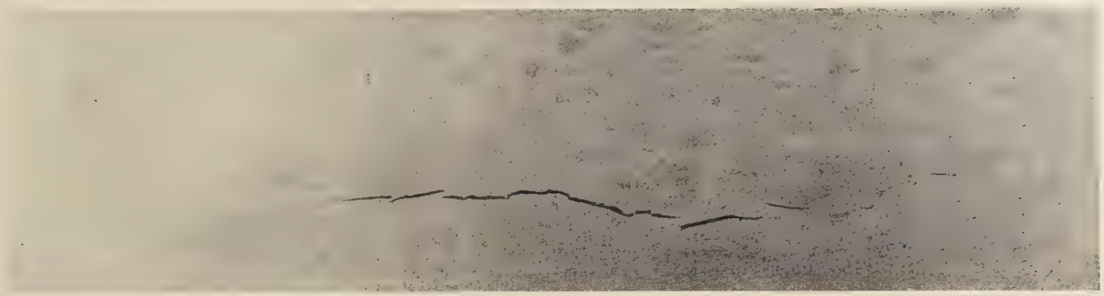


FIG. 22.—Internal Crack in Forged High-Alloy Steel.

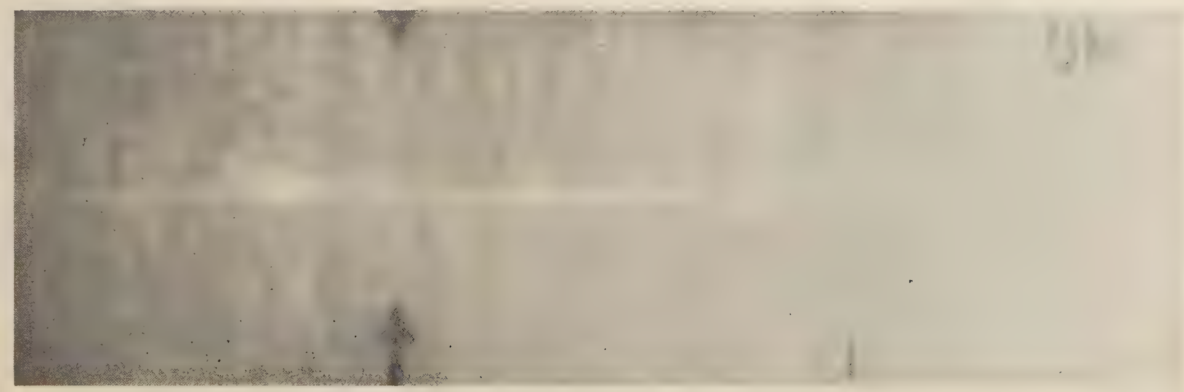


FIG. 23.—Portion of Radiograph Positive from Butt Weld on 1½-in. Mild-Steel Plate, showing central crack.

FIG. 24.—Macro-Etching of Small Flaw in Forged Bar. × 10.

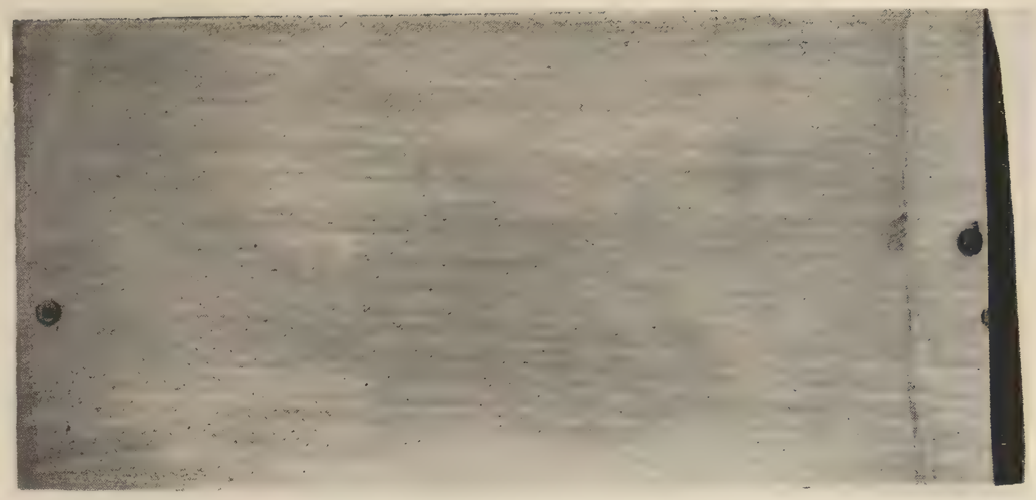


FIG. 25.—Minute Hair-Line Cracks in $2\frac{1}{2}$-in. Plate, undetected by the supersonic method when using a frequency of $2\frac{1}{2}$ Mc./sec., but revealed by magnetic etching.

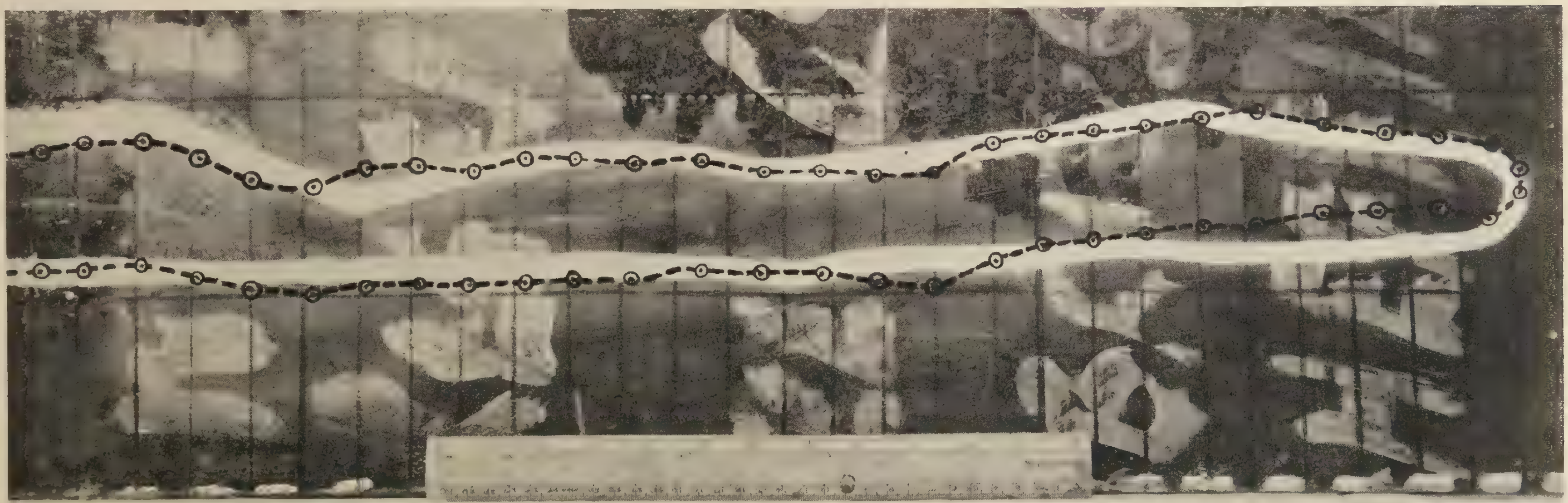


FIG. 26.—Lamination in 0·33-in. Steel Plate, detected by supersonic testing (white line) and confirmed by magnetic etching (black line).

[*Desch, Sproule, and Dawson.*

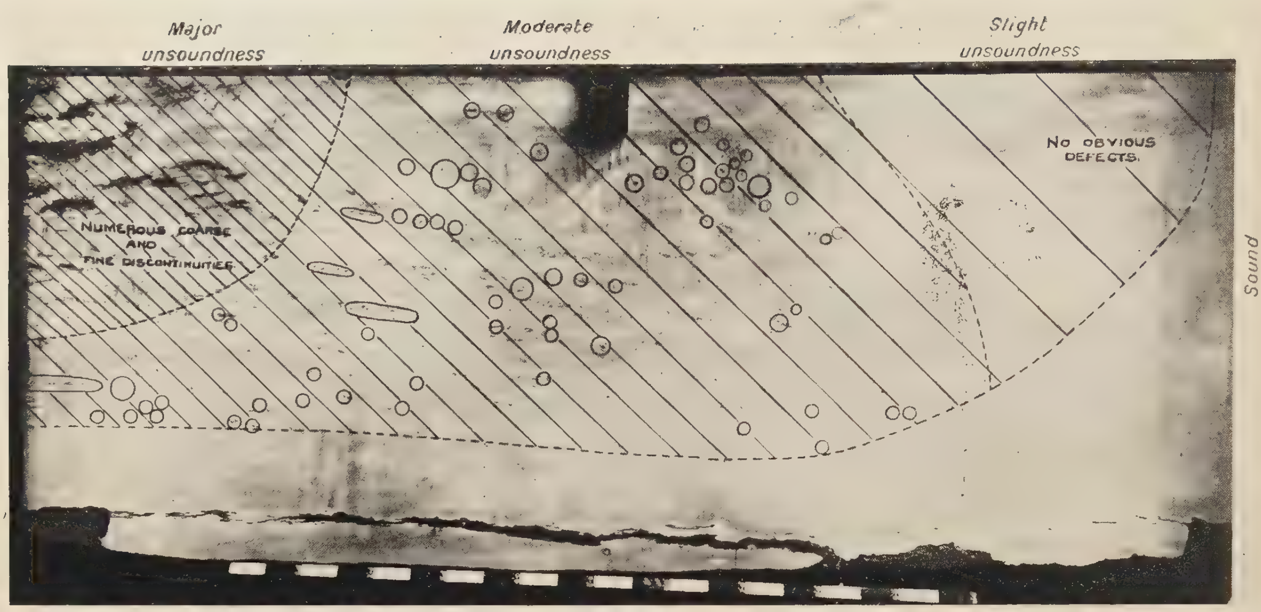


FIG. 27.—Quarter-Section of a $10\frac{3}{4}$-in. Slab, on which is imposed the general nature of supersonic results when tested from the surface before sectioning.

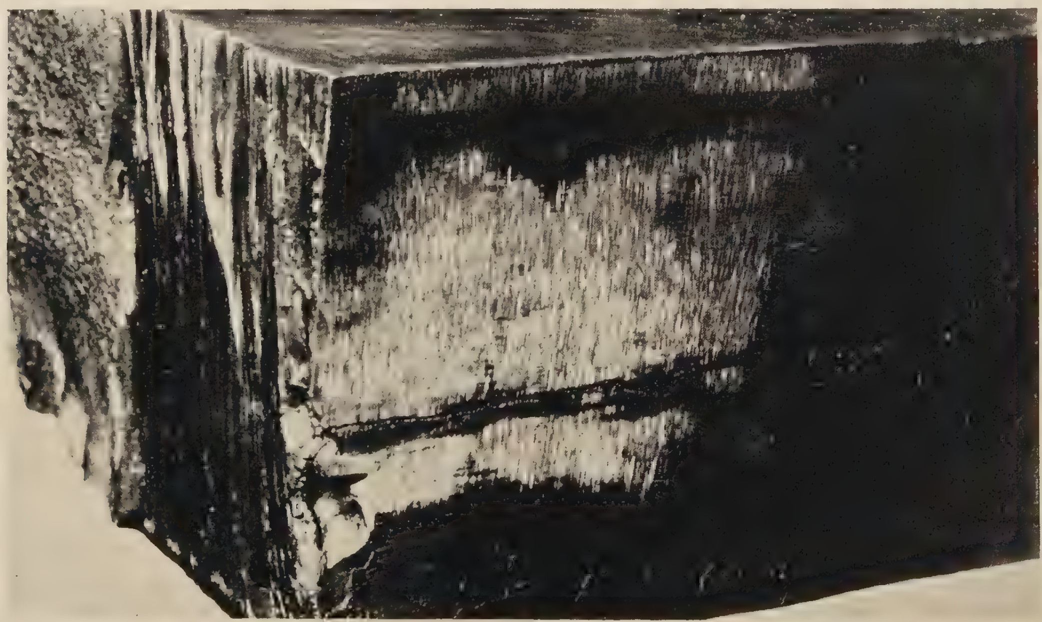


FIG. 28.—Cracks in $4\frac{1}{2}$-in. Plate caused by Flame-Cutting. Detected by supersonics and later rendered visible by light grinding of the side surface.

[*Desch, Sproule, and Dawson.*

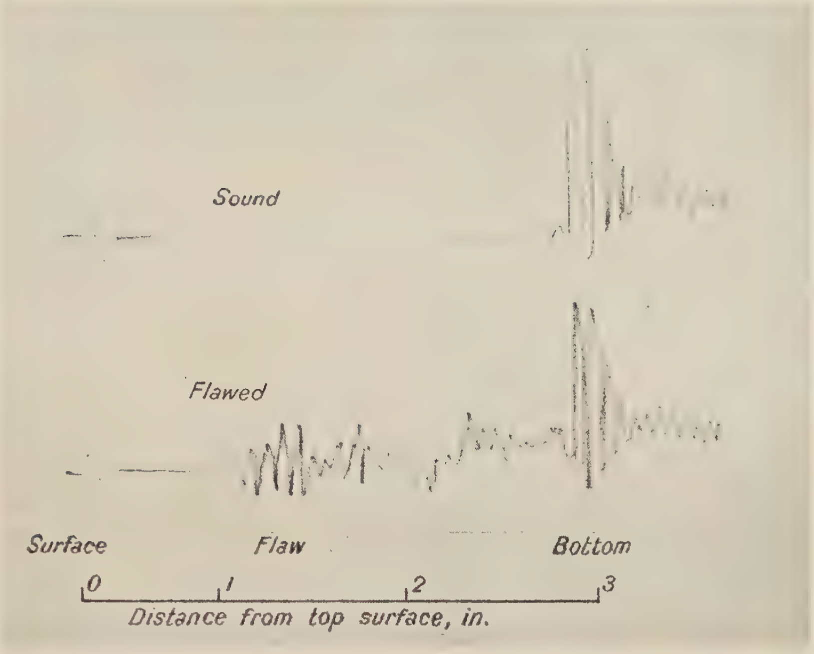


Fig. 29.—Supersonic Test on Pulley Casting.

Fig. 30.—Section of Pulley Casting, showing porosity.

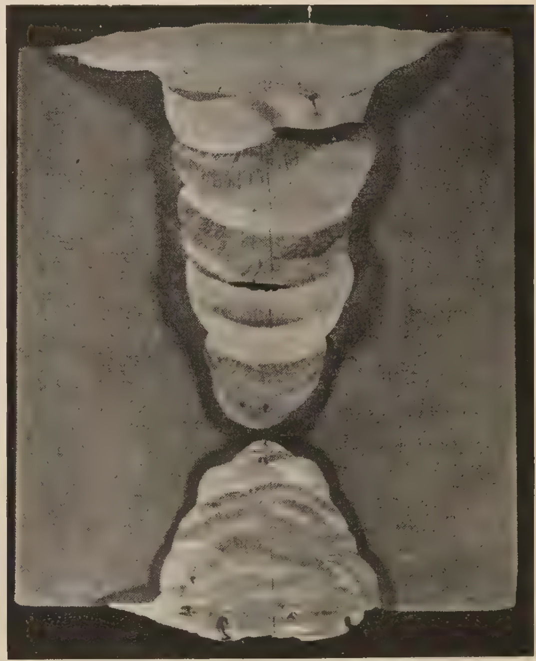


Fig. 31.—Butt Weld on 3-in. Low-Alloy Steel Plate, showing entrapped slag. (Actual size.)

[*Desch, Sproule, and Dawson.*

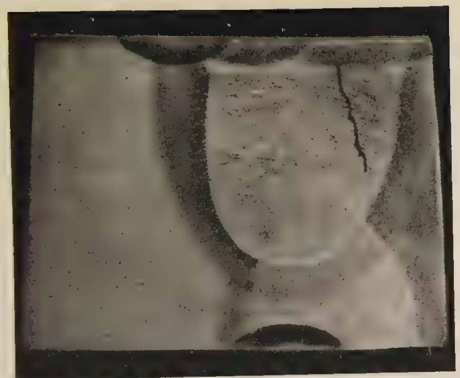


FIG. 32.—Section through Weld shown in Fig. 23, showing crack. (Actual size.)

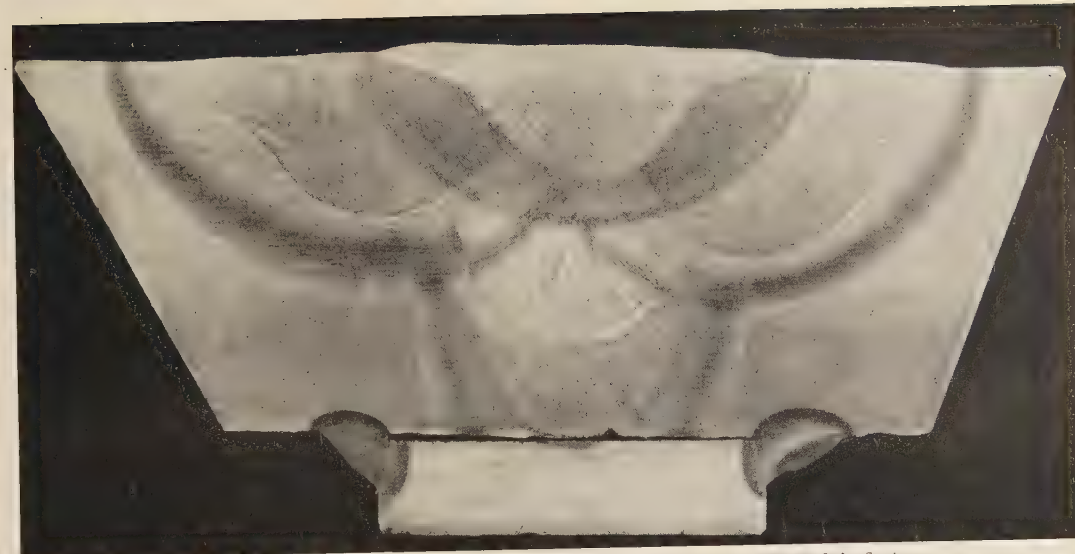


FIG. 33.—Butt Weld on 2-in. Low-Alloy Steel Plate, showing vertical crack in first run. (Actual size.)

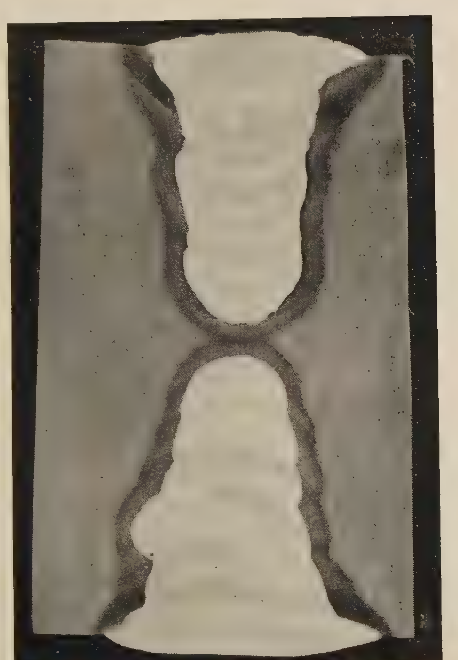


FIG. 34.—Butt Weld in 3-in. Low-Alloy Steel Plate, using stainless-steel electrodes, showing interfacial defect.

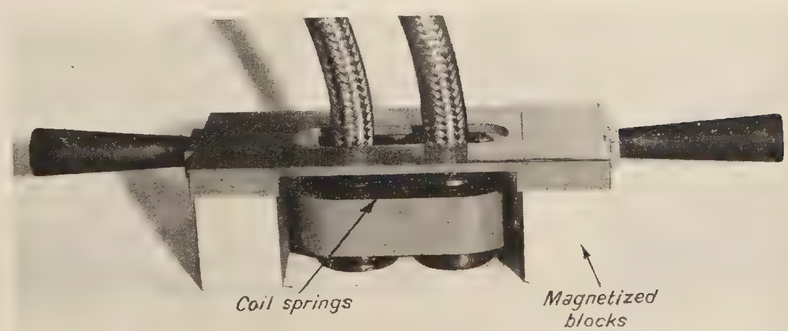


FIG. 35.—Single Magnetic Probe Holder.

[*Desch, Sproule, and Dawson.*

[*To face p.* 329 P.

Section 3.—Application of Supersonic Testing to Steelworks Problems.*

By W. J. DAWSON, A.Met. (Messrs. Hadfields, Ltd., Sheffield).

(Figs. 17 to 35 = Plates XXV. to XXX.)

Part I.—Foreword.

The object of this section of the paper is to survey the results of investigations into the application of supersonic testing to steelworks practice, and to determine the scope of the method and the validity of the indications obtained, as a practical form of non-destructive testing.

When instruments of the first standard pattern were made available to a number of steelworks laboratories, it was arranged to exchange experiences obtained with the instruments, and to collaborate with the makers by bringing to their notice the opinions of the users on various technical features of the apparatus. By this means, operative technique would be advanced, and the instrument design directed along those channels which might offer the most fruitful scope for the development of this method of testing.

A wide range of applications in the steelworks was explored, so that it was possible to arrive at some assessment of the value of the method. As a result of the collaboration between the representatives of the maker and the steelworks laboratories, improvements in certain technical features of the instrument, and in the technique of practical operation in service have been made which have extended the scope and increased the sensitivity of the instrument.

Observations from practical work with this instrument are discussed in the present section, and the value of the test has been assessed upon a practical basis. It must be stressed, however, that, whereas much information of a useful nature has been obtained by this method of testing, there has been little opportunity yet for work to be done to correlate the results of this test with the subsequent behaviour of the material in service. Until these relationships have been established and a quantitative measure of service can be estimated by supersonic examination, this technique should be regarded as a means of specialized examination and not of inspection. This phase of the development will undoubtedly take some time, for it involves observation of ultimate performance, an undertaking which from its nature must be scattered and delayed.

The contributors who have undertaken this work and submitted the results upon which this section of the paper is based, are as follows :

Mr. J. Glen, B.Sc., A.R.T.C., Messrs. Colvilles, Ltd.

Mr. H. Nicholson, A.Met., English Steel Corporation, Ltd.

Mr. L. Rotherham, M.Sc., F.Inst.P., The Brown-Firth Research Laboratories.

Mr. W. R. Yates, B.Eng., Messrs. Hadfields, Ltd.

Mr. G. T. Harris, M.A., F.Inst.P., Messrs. Wm. Jessop & Sons, Ltd.

Mr. W. C. Heselwood, B.Sc., A.Met., The United Steel Companies, Ltd.

Subject-matter for the above contributors has been submitted in certain instances by contributors other than those taking over the responsibility for the writing of the individual sections, the task having thus been a truly co-operative one. Part V. has been compiled from the collective opinions of the investigators.

Part II.—The Technique of Supersonic Testing.

Since the earliest sets were made with the object of detecting the type of discontinuity in steel known as hair-line cracks, a frequency convenient for this purpose was chosen. Under these conditions, however, many other types of defect have been located.

An initial problem was to establish :

(i) The maximum and minimum distances at which it was desired to detect defects.

(ii) The maximum and minimum size of flaw to be detected, and—the associated problem—the minimum size of flaw capable of affecting the particular properties of the material requiring consideration.

(iii) The length of the transmitter and receiver leads necessary to permit a survey of cases likely to be met with in practice.

Target.

In regard to the above points, experience has shown that many problems may be approached if the instrument is capable of covering a distance range of $\frac{1}{2}$–50 in., though for special purposes it might be desirable to examine steel at distances as great as 20 ft. The application of the method to sheets and plates at thicknesses of less than $\frac{1}{2}$ in. had been envisaged, but it was evident that such a problem required the provision of technical features which could not be incorporated in the existing instrument.

* Received January 8, 1946.

The maximum size of target encountered was that occurring in the lamination of plates, in which case the target might be several feet across. The minimum size of target was about $\frac{1}{16}$ in. in linear dimension, when about 2 in. from the surface.

Probes.

The character of the probes is bound up with the question of the general arrangement of the instrument, and whether it has to be regarded as a laboratory instrument or as a mobile unit suitable for use in the workshop. Experience had shown that increasing the length of the probes from 3 to 4 ft. had met most requirements so far apparent.

Some difficulty was experienced initially in the positive interpretation of the trace on the screen, as a variation in pressure on the probe system caused a marked variation in the intensity of the echo. This effect has been found to be due to the use of a very thin diaphragm which buckled under pressure, and the remedy has been indicated accordingly. Owing to this variable area of contact and also since the direction of the flaw is unknown, it is difficult to estimate the area of the discontinuity in the material.

General Design from the User's Standpoint.

The first model, primarily intended as a laboratory instrument, has been used, with certain precautions, as a works instrument. The two components, the transmitter and the receiver sets, whilst too heavy to be carried readily for any appreciable distance, are sufficiently robust to enable them to be transported in the works on a well-sprung trolley. The cathode-ray tube may be viewed in full daylight, provided that a suitable screen is mounted for viewing purposes. The general arrangements of power required are only those of an ordinary A.C. point, although a reasonably stable voltage is needed to maintain a steady trace. Photography of the trace is practicable with a suitable camera.

The apparatus must be close to the object under examination by reason of the length of the leads and the need for close observation of the cathode-ray tube.

Improvements had been made in the instrument in the course of the exploratory period discussed. Prominent amongst these was an input filter, designed to reduce transverse disturbance and to enhance the echo at the fundamental frequency of $2\frac{1}{2}$ Mc./sec. This increased the sensitivity of the instrument and assisted in the examination of sections of greater depth where the transverse waves were troublesome. With some investigators the filter was found to be necessary for depths greater than 2 or 3 in. Occasionally, random scattering had been experienced, but observation of results with and without the filter had been found useful. In the case of small targets, as, for example, in detecting minute pipe in heavy plate, no results could be recorded without the filter. The filter had also been found to be of great use for testing 12-in. dia. bars for porosity.

The original time base was designed for the examination of thicknesses up to 12 in. This limitation has been overcome by a modification to the time base, and it is now possible to explore depths extending to 12 ft.

Preparation of Surfaces.

The usefulness of the instrument at the outset had been somewhat restricted by the necessity of having a smooth flat surface prepared on the material to be examined, but subsequent investigations had enabled curved and even rough surfaces to be used also. This aspect of the subject has been treated in some detail in the subsequent sections.

Types of Defect Discernible.

The frequency of the supersonic wave determines the size of discontinuity which can be detected. Thus, in ingots and large sections which have suffered little reduction by forging or rolling, or in castings, "looseness" or porosity may be observed. In forged or rolled material, any reflections observed are of significance, and the nature of the defects may be assessed by a knowledge of the history of the steel. In these respects particularly, the frequency is of prime importance.

For the purpose of calibrating the instrument to permit adequate location of defects, slabs were prepared of $\frac{1}{4}$–6 in. in thickness, and the distance between the point of initial impulse and the surface giving rise to the bottom echo was measured. The relationship between the depth of the specimen and the length on the time base is almost linear when the depth is properly focused. Small holes were drilled in a slab at different depths, and the estimated depths were plotted against the measured depth. When the correction for the thickness of the wedge was made, the estimated depth was found to be within $\frac{1}{4}$ in. of the known depth. This calibration is required for each set.

In the standard type of instrument used in this exploratory work, the wave propagation takes place in a cone with an 8° angle of spread. This means that with a 40° angle of wedge, focusing is practicable to within $\frac{1}{2}$ in. of the surface. Theoretically, signal strength should be reduced by increasing the length of the leads because of the greater capacity thereby introduced, but in practice this effect was found to be negligible, and leads up to 6 ft. in length have been used.

With a wavelength of 2 mm., a hole of $\frac{1}{32}$ in. in dia. was ultimately detected at a depth of 8 in.

Further information on the limits of sensitivity of detection will doubtless emerge as the method is applied to a wider range of problems. Where a mass of discontinuities is encountered, as, for example, in certain types of ingot structures, or in a very badly flawed billet, the strength of the signal is lost, and even the bottom echo is not discernible, owing to dispersion of the incident or reflected wave. Thus the absence of a bottom echo may be an indication of the presence of defects, but it does not indicate their depth or nature. This random scattering may not be observed with lower frequencies.

Non-Metallic Inclusions.

In general, non-metallic inclusions are not indicated by the supersonic method of testing. Reflection of large individual inclusions has been observed in circumstances in which the area normal to the wave is appreciable.

Part III.—Practical Observations on Supersonic Testing.

A.—*Testing of Large Masses.*

(Contributed by H. Nicholson and L. Rotherham.)

In the course of routine inspection or in special investigations, it frequently occurs that a knowledge of the condition of internal soundness is of considerable value. Supersonic or echo-sounding principles have been applied already to a variety of steel forgings and castings of appreciable size, and much useful information has been obtained. In general, it can be said that every such case requires special and individual consideration, owing to the diversities in shape and size amongst the larger masses. Parts such as shafts and large billets are eminently suited to supersonic testing on account of their uniformity of section, but there are many parts of over 12 in. in cross-section which are, of necessity, irregular in form, and in these instances comprehensive testing is considerably restricted. Here, localized scanning can yield valuable information, especially if carried out in zones of known susceptibility to internal unsoundness, and in the selection of such positions a sound metallurgical knowledge of the part in question is of the utmost value.

The application of supersonic testing to large masses has required certain modification of the original instrument. The extension of the time base has permitted greater penetration, while the tuning of the amplifier has served to reduce the transverse waves and to eliminate pulse noise, and has enabled longer probe leads to be used.

In many instances it has been necessary to operate the instrument in restricted spaces and in different parts of a works, owing to the difficulty of moving large masses, and here, relative compactness and portability have been a considerable advantage.

Some Examples of Large Masses of Steel Tested with the Supersonic Flaw Detector.

A number of forged blocks, approximately 15 × 15 × 17 in., were examined with the flaw detector, their thermal history having suggested that internal cracks might be present. Reflections were obtained from the bottom after modifying the time base to extend its range of depth, and there were also several reflections of considerable strength from various points inside the metal. These reflections, which denoted hair-line cracks, were found to a greater or smaller extent in all the suspected blocks, but not in a block whose thermal history had been normal.

Several hammer tups of 2 ft. cube to 3 ft. 6 in. cube, all made from the same ingot, were examined. Etching had shown hair-line cracks meeting the surface, and the flaw detector showed many such cracks inside most of the tups, though one was found to be practically free from cracks. A strong echo was obtained from the central bore of the tup (a few inches in diameter) when the probes were vertically over it, but where the bottom surface was considerably inclined to the top surface, the bottom echo was weak or non-existent over a large area. Near the edges, however, the sides reflected the waves back to the receiver, enabling a bottom echo to be obtained. The main use of the bottom echo is to show that the depth range of the time base is suitably set and that the sensitivity is sufficient; once these are known, the absence of a bottom echo due to geometrical effects alone need not prevent the effective testing of the material.

In testing large steel masses where the length greatly exceeds any other dimension, the labour involved in testing the whole volume of the steel can be reduced considerably by testing from the end face, provided that the flaws to be detected present a sufficient area as seen from the end face of the piece. Two die blocks, approximately 16 × 16 × 54 in., were tested in this way. A major crack had been found in each of the blocks when the impression was cut out, and the flaw detector was used to determine whether the crack visible on the surface extended far into the interior. In each block it was found that the crack covered almost the whole cross-section. A bottom echo could be obtained only with the probes at the edges of the end face, and a strong echo was received from the crack. The test was repeated from the opposite end, giving the same results. Thus each of the blocks contained a completely internal clink.

An interesting example of an alternative method of testing for an internal clink is illustrated in Figs. 17, 18, and 19. A die block, 15 × 16 × 60 in., was examined with the flaw detector on one of the long faces, as shown. A transverse crack was visible on the exterior surfaces at 15 in. from one end, but the supersonic test showed that there was also a completely internal clink at a position $17\frac{1}{2}$ in. from the opposite end. Immediately over the clink there was no bottom echo at all, the crack apparently serving to dissipate or scatter all transmitted energy. It was found possible to plot the position of the clink by this method, and the results are shown in the photographs. Fig. 17 shows the method of testing, and the results obtained from various representative positions in the vicinity of the internal clink. Also evident in the traces are indications of hair-line cracks within the central zone of the block. Fig. 19 shows the coincidence in the estimated and actual positions of the clink after half-sectioning.

Each case for examination has to be taken on its own merits, and in order to obtain the most informative results possible, it may prove necessary not merely to devise a particular method of approach, but to modify, to some slight degree, the supersonic instrument itself. An example of this occurs in the case of two rotor shafts, 15 ft. long × 18 in. maximum dia., which were suspected of having internal clinks similar to those found in the die blocks. The flaw detector was applied to one of the end faces with oil as the coupling medium, the quartz disc being placed directly on the steel; using the $2\frac{1}{2}$-Mc./sec. filter in the receiver, only an extremely weak bottom echo was obtained. However, by changing the output valve of the amplifier for a more sensitive one the sensitivity was increased about threefold, and by putting a tuning coil in the transmitter circuit a further fivefold increase was obtained. With this arrangement strong bottom echoes were obtained so that testing for flaws could then proceed.

No major flaw echoes were found so there were apparently no clinks. Small echoes were obtained, however, in large numbers near the beginning of the trace, at maximum sensitivity. They were evenly distributed both over the cross-section and in depth, and their amplitude decreased as their depth increased, becoming too weak to register beyond about 3 ft. A similar trace was obtained when testing from the opposite end, showing that the sensitivity, in terms of amplitude of echo from a flaw of given size, decreases appreciably as the distance increases, because of the spreading of the beam. Possibly some form of automatic gain control, operated by the time base, could be used to give constant sensitivity with variation in distance.

Examination of these echoes with a faster time-base range showed that the wave-train of an echo had a rather sharp front, like that of a bottom echo, and unlike that of an echo from clouds of fine porosity. Also, a slight movement of a probe would make a considerable difference to the strength of an echo, suggesting that the flaw was planar in shape rather than spherical. Unfortunately, there was no spare material which could be cut off for further examination, and in view of the greatly increased sensitivity of the apparatus, the size of the flaws could not be estimated reliably. It has been suggested that they were non-metallic inclusions.

Conclusion.

The examples quoted show that developments in supersonic technique have now made available to the investigator an additional source of information, but conditions peculiar to large masses can arise which considerably influence the results obtained. With large steel parts, it is well known that there is an almost proportionate increase in heterogeneity with size, and the high degree of sensitivity shown by the supersonic instrument can result—unless such features are taken into consideration—in an erroneous interpretation of unavoidable trivial irregularities, the presence of which is in no way detrimental to the service of the article in question.

The determination of the type or nature of an internal defect, as distinct from its location, is still a matter for further research. Much information is being obtained, however, from a correct interpretation of the pattern of the resulting trace. The form and permanency of the signal itself, the behaviour of the bottom echo, and the area of specimen over which the signal is obtained, are some of the features of assistance in this direction.

At the present stage of development it can be said that in the supersonic flaw detector there are possibilities not previously available for the determination of internal imperfections in large masses; but a full investigation of its potentialities, as yet incomplete, would seem to be necessary before the instrument could be considered as a standard tool of inspection.

B.—*Testing of Billets and Bars.*

(Contributed by W. R. Yates.)

The supersonic method lends itself especially to the testing of rolled and forged material. Hair-line cracks, which are an occasional type of defect occurring in this class of product, are readily detected by supersonic examination. As a routine test for billets and bars this method is more positive for determining freedom from this defect than sectioning followed by magnetic

etching. In this test a known volume of the steel is examined, whereas the method of sectioning followed by magnetic etching shows only one plane which may not be representative of the whole length of the mass in question.

The material may be tested by selecting various bars representative of the cast and preparing surfaces on the portion to be examined by grinding or machining or, alternatively, specimens cut from the bars may be prepared and examined by the apparatus in the laboratory.

In this class of forged or rolled material it is desirable to obtain some idea of the nature, magnitude, and orientation of flaws indicated by reflection of the supersonic wave.

Accuracy of Location.

An example occurred in a $6\frac{1}{2}$-in. sq. billet, where a single hair-line crack was located, and upon sawing at the position of the flaw a crack was seen in one face only; the calculated position was within $\frac{1}{4}$ in. of the actual position. The length of the hair-line crack was found to be $\frac{1}{4}$ in.

Magnitude of Flaws.

The minimum size of flaw detectable will depend upon the surface area capable of reflecting the supersonic wave. An example of a small single flaw in a specimen of austenitic steel is shown in Fig. 24, which is a macrophotograph at a magnification of 10 diameters. This small crack, $\frac{1}{40}$ in. in length, was found at a depth of $1\frac{1}{4}$ in. from the surface of examination. Clusters of inclusions or segregates, whilst probably of smaller individual area, have been detected owing to the total surface area becoming appreciable.

Orientation.

Where the specimen is of circular section, the probes may be rotated until the position of maximum reflection occurs, indicating the position where the greatest surface area is reflecting the supersonic wave to the receiver. In material of rectangular section, the examination is limited to two directions at right angles, and hence the orientation of an internal crack can be determined only approximately.

Nature of Defect.

In rolled and forged material the following types of defects have been observed: (*a*) Hair-line cracks, (*b*) internal cracks, (*c*) segregates, and (*d*) piping. Where it is possible for two or more of these types of defects to be present in the specimen under examination, it is desirable for the observer to be able to distinguish between the different types of flaws. Internal cracks, (*a*) and (*b*), can usually be distinguished from segregates and piping, (*c*) and (*d*), by the scattering along the length of the bar or billet and by the position of the defect or defects in the section. If the specimen is of circular section, rotation of the specimen is usually sufficient to distinguish between cracks and segregation, the echo vanishing when the supersonic wave travels along the plane of the crack. In general, as experience is gained with different types of defects and the flaws are subsequently examined by other methods, the diagnosis becomes more reliable.

Hair-Line Cracks.

A typical photograph of hair-line cracks in a 6-in. sq. billet after fracture is shown in Fig. 21. These cracks have an appreciable surface area and can be readily detected by the supersonic flaw detector when examined from a surface parallel to the plane of the crack. These cracks, however, are of small width, and cannot be detected from a direction in or near the plane of the crack, the intensity of the echo diminishing as the angle between the planes of the crack and the surface of examination increases. If the examinations are made from two directions at right angles, any crack present will almost certainly be detected.

Investigations into the problem of hair-line cracks have been assisted by the supersonic flaw detector, and it has been found that continuous examination of a test-specimen which had been air-cooled after rolling enabled the incubation period, *i.e.*, the period between rolling and the appearance of the first flaw, to be determined accurately. Diagrams drawn during subsequent examination show the order in which the flaws continued to develop. An example of this is given in Fig. 36, which shows the positions of flaws detected by examination from two adjacent surfaces. Development over a prolonged period does not appear to follow any order, but provides information suggesting the steady development for 50 hr. after an incubation period of 20 hr.

An instance has occurred where the supersonic test revealed hair-line cracks in a forged disc which had previously been reported sound after magnetic etching. A slice was cut from the disc parallel to the plane of the cracks resulting from forging. Polishing before etching removed the cracks, and hence the magnetic-etch test failed. Supersonic examination from the etched face revealed the cracks clearly since they were in a plane parallel to the surface from which the examination was made.

Internal Cracks.

In the further processing of forged bars of an austenitic-type steel, certain failures were observed; bars were therefore examined by the supersonic method and certain reflections were observed at several positions. After slicing along

the diameter and etching, internal cracks were seen at the position indicated by the echoes, a photograph of which is shown in Fig. 22. Although the percentage of this class of material which was found to be defective was small, the removal of the defective portions enabled further processing of it to be avoided.

Cracks Due to Cooling Stresses.

A 3-in. sq. billet of $4\frac{1}{4}$% nickel–chromium steel, air-cooled from the rolling temperature, contained a major crack stretching from a surface nearly across the full width of the billet. A pronounced echo to the left of the bottom echo was

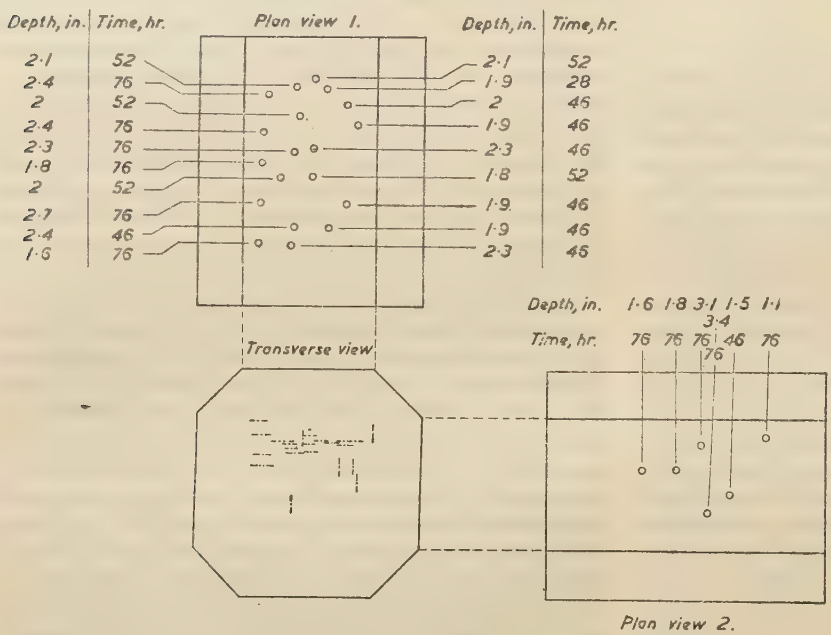


FIG. 36.—Development of Hair-Line Cracks with Lapse of Time.

obtained when testing was carried out across the crack. No reflection from it was obtained when testing was carried out along the crack.

Segregates.

Eight-inch diameter forged bars of a high-alloy steel were known to contain segregation over a certain portion of their length. It was found that an accurate estimate of the length of discard necessary could be made by supersonic examination. Since the echoes from the segregated areas were of great amplitude, the examination could be made rapidly.

Piping.

A sample of high-alloy steel bar containing pipe gave a strong reflection midway along the trace, as shown in Fig. 20(*c*). A similar bar which was of the same size and composition but unpiped, gave a clear trace before the bottom echo. The photographs of the traces indicate the magnitude of the reflected wave from the pipe.

C.—*Testing of Slabs and Plates.*

(Contributed by W. C. HESELWOOD.)

Much of the supersonic testing of slabs and plates is essentially similar to that already described for other shapes, particularly that of billets and bars, since a slab or plate might be considered as a rectangular billet or bar having one small and two large dimensions. Such applications will not be described again here, except insofar as reference may be made to specific examples of particular interest.

Hair-Line Cracks.

(i) *General.*—The examination of slabs and reasonably thick plates (greater than about $\frac{3}{4}$ in.) for hair-line cracks is quite practicable by the method already described for billets and bars. The hair-line cracks, if present, lie in planes parallel to the plane of rolling, and in this case the lesser practicability of testing in two directions at right angles is therefore not of importance. The tests are carried out in the usual manner, working with both probes (with or without wedges, according to the thickness) on the same surface.

(ii) *Hair-Line Cracks Present, but not Detected by the Supersonic Method.*—It is important to record an interesting example of the apparent failure of the supersonic method; the term "apparent failure" is equally important, for there was a perfectly good reason for the negative result, which in turn emphasizes the undesirability of supersonic testing being indiscriminately employed by untrained personnel.

The subject was a $2\frac{1}{2}$-in. dia. alloy-steel plate, in which minute hair-line cracks were revealed by the magnetic etching of a cross-section (Fig. 25, actual size) but which showed nothing, other than the bottom echo, when tested by supersonics.

The reason was that the diameter of the cracks was considerably smaller than the wavelength of the supersonic beam employed. Further reference to this point is made in Section 2 of this paper.

Laminations in Plate.

A particular trouble associated with steel plate

is the presence of lamination, due, for example, to the rolling-out of pipe incompletely removed from the original ingot. A portion of the plate contains a plane of separation lying parallel to the plane of rolling and usually occurring approximately midway across the thickness. This is a major defect, and in the thicker sections (about $\frac{3}{4}$ in., upwards) a plate can be explored from one surface by normal methods.

For thin plate, a more certain method is to carry out the test by transmission, *i.e.*, by holding the transmitting and receiving probes opposite each other on each side of the plate. If the plate is sound, a strong signal is received, but if laminated, the signal is considerably reduced in intensity and usually completely eliminated. The result of a particular test on a piece of 0·33-in. plate is shown in Fig. 26. This plate was explored by the supersonic method, and the laminated area so determined was outlined with white paint and photographed. The plate was then sectioned into strips and the limits of the lamination determined by magnetic etching; these results are superimposed on the photograph (Fig. 26). The actual experimental points are shown encircled, and the agreement is seen to be quite good; the differences are within the limits to be expected with the size of exploring probes used.

It is not difficult to construct special tongs to hold the probes correctly on either side of the plate. Also, it is fortunate that the as-rolled surface of steel plate is normally good enough not to require any special preparation.

Composite Plate.

In composite plates consisting of two materials (*e.g.*, mild steel and stainless steel) welded together, there may be areas over which adhesion is poor. The problem of detecting such areas is essentially the same as that of detecting lamination, and the same methods may be used.

Examination of Thick Rolled Slab.

A $10\frac{3}{8}$-in. thick slab had shown extensive axial cavities after removal of the "top" discard, and supersonic testing was resorted to in the determination of the extent of penetration of this unsoundness, with a view to utilizing the sound portion of the slab.

The entire surface of the slab was supersonically tested after machining. Over the top central portion, where no bottom echo could be obtained, major defects were presumed; over a considerable extent of the remaining surface there was evidence of numerous small discontinuities, while towards the extreme bottom end, only traces of discontinuities were indicated.

A quarter longitudinal section of this slab gave good confirmation of the supersonic estimate, as shown in Fig. 27, in which an indication of the supersonic results is shown superimposed on a photograph of the section. The discontinuities found in the area of lesser unsoundness are on the whole of a small order, and those associated with the primary segregation there are merely incidental, their presence in a mass of this nature being virtually unavoidable.

The area of slight responsiveness at the "bottom" end showed no discontinuities on half-sectioning, but, quite possibly, irregularities of an extremely small order may have been present elsewhere, through the thickness of the slab at this position.

Here is an instance, therefore, where negligible irregularities in a large mass are clearly recorded supersonically as a result of the use of an instrument having a high degree of sensitivity; the need for discriminate interpretation of the results obtained, with consideration of the nature of the specimen is once again emphasized.

Detection of Cracks Caused by Flame-Cutting.

This is an example of a general nature. When examining a $4\frac{1}{2}$-in. alloy-steel plate which had been flame-cut, strong reflections revealed the presence of a crack that had been produced by the stresses set up during flame-cutting. The crack was made visible on lightly grinding the side surface (Fig. 28).

D.—*Testing of Castings.*

(Contributed by G. T. Harris.)

The supersonic flaw detector has been applied to the examination of a variety of castings, and some of the observations made are recorded below. In general, it has been found that the flaw detector has been of use in the examination of castings for areas of porosity and internal cavities, provided that these areas are of appreciable size. In certain cases, particularly on ingots, results have been negative, apparently owing to the general looseness of the structure.

Examination of cast armour plate has been found to yield information on the location of areas of porosity. After preparing the surface of a 20-mm. thick, cast plate on a shaping machine, a defective area was revealed, at approximately half depth, which could be traced satisfactorily, and subsequently confirmed by an X-ray radiograph. Examination of a cast-steel tank turret, with an average thickness of the order of 5 in., enabled the position of certain shrinkage cavities, due to inequality in section, to be mapped out. Preliminary examination carried out from the machined top surface gave the approximate position of the defects, which were subsequently located more precisely by examination from the surface of the casting. In this case the surface was not specially prepared, contact being estab-

lished by means of plasticine, and using the technique described in Part IV. Although the areas were located, they were considered to be of the order of only $\frac{1}{4}$ in. in dia., and subsequent firing trials showed no detectable difference in the ballistic properties. It was evident, however, that the method would be of great use in the examination of such castings for location of shrinkage cavities.

In certain cases it has been found that, owing to the generally more open structure of castings, better results can be obtained using a lower frequency of supersonic wave in order to reduce the general scattering. For instance, examination of a casting varying in thickness from $1\frac{1}{2}$ to 3 in., using the bare quartz on flat smooth surfaces demonstrated that, with the $2\frac{1}{2}$-Mc./sec. filter, no clear bottom echo could be obtained at certain parts of the casting, but that this difficulty could be overcome by the use of a 0·8-Mc./sec. tuned circuit in the transmitter. Variable results have also been obtained on the estimation of the chill depth of chilled cast-iron rolls. Preliminary results were promising, but a further examination of the problem showed that in its present form the supersonic method could not be considered reliable, probably owing to the " looseness " of the cast structure. In this case, again, it is possible that further progress might be possible by the use of supersonic waves of lower frequency and correspondingly longer wavelength. Similar difficulties have been observed in the examination of large ingots in which it has normally been found impossible to obtain any definite indication of an echo either from the bottom or from internal free surfaces. This applies even when a corner is planed at 45° in order to project the supersonic beam along the primary dendrites, and it is evidently due to complete internal scattering of the beam.

Successful results have been obtained with the method in the examination of cast-iron castings, provided that the casting has a sufficiently large flat surface on which the probes can be used, and that the metal thickness is greater than about $\frac{1}{2}$ in. In such cases, the method has proved of considerable value, and little hindrance has been found from the presence of the usual graphite flakes in cast iron. In a particular case where it was thought that reflections were being obtained from the graphite, a microsection indicated the presence of scattered porosity, which was presumably the cause of the observed echoes. A typical example of a successful application of the method to cast iron is illustrated in Figs. 29 and 30. Fig. 29 shows a pencil tracing taken from the screen during examination of a pulley casting of approximately 3 in. thickness. The material was found to be largely sound, but a particular part gave strong indications of a fault at an estimated depth of $1\frac{1}{4}$ in.; this was confirmed by subsequent sectioning, as shown in Fig. 30. This application has proved of some interest, as examination of such components was previously impossible, and defects near the bore were discovered only on final machining.

E.—*The Testing of Welds.*

(Contributed by J. Glen.)

The chief defects which may arise in welded steel structures are slag entrapment or blowholes in the weld metal, and cracking either in the weld or in the thermally disturbed zone of the parent plate.

At present, the principal method of non-destructive testing of welds is radiography, but this method requires that the defect extend through at least several per cent of the plate thickness; also, as the plate thickness increases, very powerful equipment is necessary to reveal defects.

Material and Apparatus.

The material consisted of steel plate of 1–3 in. in thickness, which had been butt-welded by the electric-arc process. It ranged from mild steel to low-alloy steel, so that the hardness at the weld junction varied up to a maximum sufficient to cause cracking. The welds were made with both ferritic- and stainless-steel electrodes.

The apparatus used was the Mark I. supersonic flaw detector, fitted with a $1\frac{1}{4}$- or $2\frac{1}{2}$-Mc./sec. filter. This apparatus is not nearly as sensitive as subsequent models of the same type.

To simplify the description of the results obtained, the data have been grouped under the type of defects, as follows :

Welds Free from Defects.

(a) *No Preparation of Surfaces.*—Using the 30° angle probes and keeping the distance between the wedges fixed so as to give the maximum bottom echo for the particular thickness of plate, attempts were made to retain the bottom echo as the probes were moved across or along the weld. Even with the liberal use of amalgam, or plasticine impregnated with oil, it was impossible to obtain any echo at all with the probes in contact with the weld-metal surface.

One other method was possible, namely, by applying the probes to the gas-cut edges of the parent plates, so that the supersonic beam travelled parallel to the plate surfaces, as shown in Fig. 37. In every case good echoes were received from the opposite edge of the welded plate. The maximum size of plate tested was 2 ft. 6 in. sq. It was thus established that the varying hardness and microstructure of the thermally disturbed zone,

and also the composition of the weld metal, did not produce severe damping or reflection of the supersonic beam.

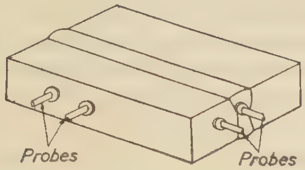


FIG. 37.—Method of Using Flat Probes on Gas-Cut Edge.

(b) *Weld Metal Roughly Buffed Flush with Plate.*—No great care was taken to achieve dead-flat surfaces. Owing to the undulating nature of the buffed surfaces, it was found necessary to use amalgam, or plasticine impregnated with oil, with the 30° angle probes. The plate was then scanned by the usual method, as shown in Fig. 38.

An echo received before the bottom echo indicates a defect parallel to the plate surface, while a diminution of the bottom echo indicates a defect perpendicular to the plate surface.

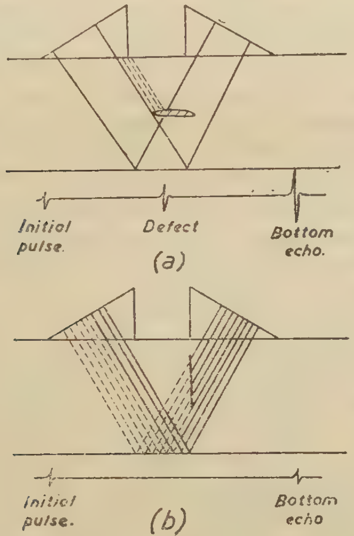


FIG. 38.—Method of Using 30° Wedges for Detecting (a) horizontal and (b) vertical defects.

Owing to the hills and hollows made by the buffing and also, in some cases, to the fact that the plates after welding were not dead flat, it was found that the amplitude of the bottom echo varied greatly, as if there were a vertical defect. On varying the distance between the probes, it sometimes appeared that there was total reflection from a horizontal defect in the weld. In effect, any result can be obtained, either through bad contact between probes and metal, and/or through slight tilting and slewing of the probes so that they are no longer parallel.

(c) *Weld Area and Adjacent Plate Surface Machined or Buffed Dead Flat.*—With proper preparation of the surface, no difficulty was found in obtaining a consistent bottom echo, thus demonstrating that the welds were free from major defects.

For the experiments given in the following description of the detection of defects, a sufficient area of the plate was machined flat to ensure reliable results.

Slag Entrapment.

Two typical examples of slag entrapment in welds were obtained :

(*a*) 1-in. thick mild-steel plate, hand-welded, using a single V-edge preparation. There was excessive slag entrapment about the centre of the weld.

(*b*) 3-in. thick low-alloy steel plate, hand-welded, using a double V-edge preparation, and stainless-steel electrodes. A section through the defective area is shown in Fig. 31.

Since the defects were essentially parallel to the plate surface, they were readily detected as an echo received before the bottom echo, as in Fig. 38 (*a*). Had they been essentially perpendicular to the plate, they would have been revealed only by a diminution of the bottom echo, as shown by Fig. 38 (*b*).

Cracking.

Typical examples were as follows :

(*a*) $1\frac{1}{2}$-in. thick mild-steel plate, welded by the electric-arc process, using a single V-edge preparation. The weld was 2 ft. long and was found to be cracked for a distance of about 6 in. from each end. A positive print from a radiograph of part of the weld length is shown in Fig. 23, and a section through the weld showing the crack, in Fig. 32.

(*b*) 2-in. thick low-alloy steel plate, welded by the electric-arc process, using a single V-edge preparation. Five runs were used to fill the V. In one area of the plate, a small vertical crack, $\frac{1}{4}$ in. deep $\times$ 1 in. long, was found in the first run of weld metal, as indicated in Fig. 33.

(*c*) 3-in. thick low-alloy steel plate, welded by using a double V-edge preparation and stainless-steel electrodes. A large crack was found at the weld junction of one side of the V, as shown in Fig. 34. This crack did not quite extend to the surface of the plate. The cracks in the weld were all essentially perpendicular to the plate surface, and thus, by the method shown in Fig. 38 (*b*), the defects were revealed only by a diminution of the bottom echo. By this method the crack in the weld shown in Fig. 33 was too small to be detected by the Mark I. equipment. Confirmation of the presence of the cracks was obtained by the method

shown in Fig. 37, the weld seam being normal to the supersonic beam. In this case, a reflection was obtained, even from the small crack present in the weld shown in Fig. 33.

Conclusions.

With the Mark I. equipment it appears that the varying hardness and microstructure of the thermally disturbed zone of the parent plate, and also the structure and analysis of the weld metal, do not cause any appreciable damping or reflection of the supersonic beam.

The first essential in the satisfactory testing of welded plates is to ensure that the surfaces of the weld and adjacent parent plate are finished dead flat. With this proviso, defects horizontal to the weld surface can be detected in the usual way by an echo received before the bottom echo. Vertical defects are revealed by a diminution of the bottom echo. They are also readily revealed in the usual way by testing from the plate edges. This method, however, is not always possible.

Considerably more work is necessary, using the most up-to-date equipment, to establish fully the above conclusions and to determine the actual size of the defects.

A great advantage of the supersonic method of testing is that very thick welds are well within its scope, and it should thus be possible to reveal flaws which the radiographic method might not detect.

Part IV.—The Technique of Surface Transmission.

(Compiled by W. R. Yates.)

As a result of close collaboration between the investigators, considerable improvements in technique have been developed. The effects of these improvements are reflected in an increase in the range of articles which can be examined with this instrument.

In order to obtain transmission of the supersonic wave from the quartz crystal to the steel, it is necessary to ensure good contact between the crystal and the steel. In the course of the application of the supersonic flaw detector to steelworks problems it was found that transmission through an oil layer on rough surfaces similar to those encountered with rolled material was unsatisfactory for the detection of defects, and presented a serious problem to the users. It may occasionally be impracticable to smooth-machine all the material that has to be tested, and the devising of alternative techniques was therefore necessary.

Preparation of Surfaces.

For the routine examination of specimens obtained from billets, the practice of machining the surface is the most satisfactory as the surface produced enables a rapid examination to be made. Where the material is of square section two adjacent surfaces are prepared in order to be sure that flaws which lie in a plane perpendicular to the surface of examination can be located; a reliable estimation of the size and character of the flaws can then be made.

Surface Grinding.

Where it is inconvenient to machine a billet of large section, the hand grinder provides a quick method of preparing suitable test-areas. At first, such tests were made with an ordinary hand grinder having a periphery-type wheel, and it was found that after a little practice a test-area could be prepared which would give usable results, and which could be further improved by the use of a sander. Later, a cup-shaped hard resinoid-bonded wheel proved much superior for obtaining a good flat test-area.

The Use of Plastics.

Numerous articles with curved surfaces require examination after machining. An adaptor which can be manufactured rapidly and which will conform to the curvature of the surface, can be made from a transparent plastic such as Perspex. Adaptors made from this material may be moulded by pressure at 135° C. A strip, $1\frac{1}{4}$ in. sq. $\times$ $\frac{1}{4}$ in. thick, is pressed on to the surface of the specimen, using a metal former to produce a cavity which will hold the probes. The pressure may be applied by a hydraulic press, *e.g.*, the crosshead of a tensile machine is sufficient, or, if the article to be examined weighs more than 1 cwt., the weight of the article is sufficient to produce the necessary curvature of the plastic. Fig. 14 (*a*) shows the application of this technique. Since each adaptor will cover a range of curvature, a series covering all ranges of curvature likely to be encountered can be made for permanent use. In common with the amalgam technique, this method reduces the magnitude of the transverse wave, so simplifying the examination of large sections.

The Use of Plasticine.

A recent innovation is the use of plasticine. This technique is of particular value for rough surfaces, even when they are not horizontal, and it is also suitable for the rapid examination of rough surfaces where the area to be examined is relatively small. The probes are covered with a layer of plasticine about $\frac{1}{2}$ mm. thick, and are then pressed firmly on the surface to be examined. The probe is removed from the surface when it has to be moved to a new position, as sliding tends to strip the plasticine.

The Use of Amalgams.

Instances occur when the specimen to be examined has a rough surface which may not be machined. A technique which enables articles with rough surfaces to be examined without preparation involves the use of amalgams. The most effective elements for this work are tin and cadmium, and the amalgams may be prepared with either or both of these elements. A suitable amalgam can be prepared by shaking cadmium and tin filings in the proportion of 6% of cadmium and 3% of tin, with mercury in a hot 10% solution of ammonium hydroxide. When complete amalgamation has taken place, the alloy is chilled and dried, and will be of a pasty consistency at 16° C. If the operating temperature is higher, it is advisable to add more tin and cadmium in order to retain the correct consistency. The amalgam should be used on a clean, dry surface to minimize contamination, and considerable pressure should be applied to fill cavities occurring in the surface. This method of examination is relatively slow compared with oil, but has the advantage that the transverse waves may be eliminated from the trace if the amalgam under the two probes is not allowed to join. The relative transmission of the supersonic wave through the mercury–steel interface is slightly less than when using oil on a smoothly machined surface, but on a rough-cast or a rolled surface, the results obtained with mercury amalgams as the medium of transmission are superior to those obtained with oil.

The Use of Magnetic Clamps for the Probes.

When using the supersonic method for detecting flaws in steel, the transmitting and receiving probes have to be held firmly in position, either directly on the steel surface for normal transmission or together with the use of steel wedges for transmission at an angle inclined to the normal.

The ordinary method has been to hold the probes in position by hand, but this is sometimes awkward, and in any case there are advantages in having the hands entirely free for other purposes. It was thought that when testing ferrous materials (other than austenitic), magnetic clamps might be useful, and this note describes what has been done in preliminary tests. These tests have established the principle using some chromium magnet steel which was immediately available, and particular designs could now be improved by the use of magnet steel possessing more powerful properties.

(i) *Clamp for Normal Incidence of the Supersonic Beam.*—The magnet can be of the horseshoe type, bridging the probe and with a hole in the centre to accommodate the flexible lead thereto. The magnet clings to the surface of the specimen under test, and a light spring between magnet and probe supplies the necessary pressure to hold the probe firmly against the surface. The principle is illustrated in Fig. 39; the unit shown was more conveniently built up, with materials available, as a composite magnet of magnet steel and mild steel, instead of using magnet steel throughout.

Using a more powerful magnet material of the iron–nickel–aluminium–cobalt type, a small, neat, and strong magnet clamp could be made.

(ii) *Clamp for Inclined Incidence of the Supersonic Beam.*—Two methods have been considered: (*a*) The use of a clamp operating as described above, but in this case pressing the wedge unit against the surface, and (*b*) making the wedges

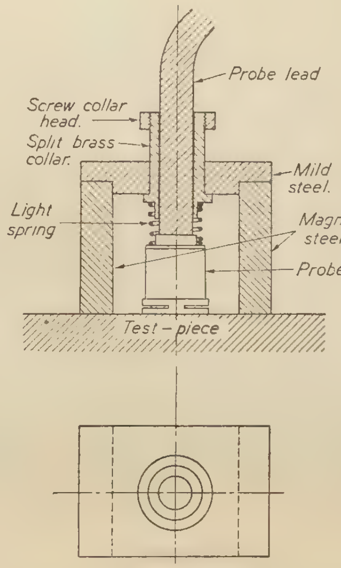


FIG. 39.—Magnetic Clamp for Supersonic Probe.

of magnet steel so that they themselves cling to the surface. Considered as magnets only, these wedge shapes constitute an inefficient design, but a sufficiently strong attractive force has been obtained for the present purpose.

A second type, in which the probes are held in a single headpiece, and hence at a fixed distance apart, is shown in Fig. 35. The clamp is made of magnetized blocks and the probes are pressed by springs on to the surface of the steel. The method is particularly applicable for the examination of large depths of material. The use of a holder simplifies photography of the trace, enabling the operator to have both hands free, and eliminates variation in pressure during the exposure.

The Probes.

Increased amplitude is achieved by the use of the quartz crystals applied directly to the specimen, eliminating loss through the oil film and the copper disc. It was found that the copper discs originally used with the instrument were

damaged by rough surfaces, causing reduction in transmission of the supersonic wave. Steel discs are now commonly used, and may be made satisfactorily up to $\frac{3}{8}$ in. in thickness.

Where contact between the quartz disc and the steel is not uniform, anomalous results may be obtained. An instance occurred where a roughly machined surface caused echoes to be distributed along the trace. The echoes were no longer present when the surface had been made smoother, and it is presumed that the echoes must have been due to the transverse waves travelling along the surface.

Part V.—Desired Features of the Apparatus.

The following observations constitute a consensus of the views of the observers (who have applied the supersonic method to steelworks problems) on the desired features of the apparatus. The suggestions are intended to indicate the limitations of the present equipment rather than to assess its merits, which must be apparent from the preceding sections. They are not intended as final recommendations, for the scope of this method of testing has not yet been fully explored, but rather as the result of observations from the work which has already been carried out with the Mark I. apparatus. The remarks may be considered separately as applying to (*a*) the mechanical, and (*b*) the electrical features of the apparatus.

(a) *Mechanical.*

Portability.—In order that the instrument may have the widest possible use in the works as a tool for making a rapid internal survey of large masses, it is essential that the set be portable. The original apparatus was housed in two cases with a total weight of approximately 160 lb. This weight has been considerably reduced in subsequent models.

Compactness.—The size of the instrument is of importance in so far as bulkiness reduces portability. However, any reduction in size and weight which involves reducing the size of the cathode-ray tube leads to increased eye strain on the observer, particularly for semi-distant viewing.

Sturdy Construction.—The construction of the equipment should be sufficiently robust to withstand the conditions likely to be encountered during transportation through the works. The danger of rough handling may be reduced by mounting on rubber cushions the trays carrying components of a fragile and delicate nature.

Waterproof Probes and Leads.—The probe leads are damaged when drawn across sharp metal edges, and they absorb oil or water from the surroundings, which is difficult to remove without stripping the insulators, and this is a tedious process. The leads and heads of the probe should therefore be armoured, and proof against penetration, especially by water which in the present design of probes is liable to result in electrical shorting and reduction of signal strength.

Calibration of Depth.—A scale on the tube, calibrated to read the depth directly for each setting of the time base, is desirable. As the characteristics of the electrical components of each set vary, and the time base over certain ranges is non-linear, separate calibration for each set is necessary.

Camera.—It has sometimes been advantageous to take photographs of the trace during examination to provide a permanent record of results. The present system, which involves setting a camera for a time exposure in a relatively dark room, is not always convenient. The proposal has been made by the investigators of having a camera which can easily be attached to the tube unit, and from which several photographs could be taken in sequence.

(b) *Electrical.*

Variable Sensitivity.—It is frequently difficult to estimate the size of the flaw detected. To overcome this an additional feature which would make possible the use of a known and variable sensitivity would be of the utmost value. The sensitivity is, in some measure, determined by the frequency, and a variable frequency within certain limits may help in determining the size of the flaw located.

Sensitivity on Rough Surfaces.—The sensitivity on rough surfaces has been improved by the use of amalgams and filters, but further improvements are required before these methods can be considered satisfactory for practical purposes.

Testing to Great Depths.—In testing to great depths, the wave-form of the echoes becomes very short and sharp, so that the trace gives reduced information about the nature of the flaw. Under such conditions the echo has to be examined under greater resolution, as in smaller specimens.

Dead Zone.—Owing to the inability with the present probes to receive reflections of the wave from discontinuities at less than $\frac{1}{2}$ in. from the surface, there is in effect a dead zone in which flaws cannot be located. A reduction in the depth of this zone to, say, $\frac{1}{16}$ in., would be desirable to enable flaws immediately below the surface to be located.

Single Transceiver.—A single transceiver in which the same quartz crystal is used for both transmission and reception of the supersonic wave, might provide the solution of the dead-zone problem, and be of additional assistance in other problems.

Scanning Mechanism.—A further long-time requirement would involve the use of some scanning mechanism, as employed in radiolocation, to eliminate the necessity of searching for defects by traversing the detector. This may or may not involve the use of a single transceiver, which is in itself a desirable feature, although there are certain occasions where it would be preferable to use separate transmitters and receivers.

Part VI.—The Function of Supersonic Testing.

It is apparent from this review that supersonic testing has so far been found capable of revealing the presence of those discontinuities in steel which are able to reflect the supersonic wave. It constitutes a new field of non-destructive investigation of the properties of the products of steel manufacture, but considerable work remains yet to be done in the correlation of the effects found and the behaviour of the article in service. Accordingly, it should not yet be regarded as a comprehensive method for the acceptance or rejection of all material.

If the results of any pertinent system of testing are properly interpreted, they can be made a valuable aid to the steelmaker in controlling the quality of his product. If they are used indiscriminately or even prematurely they can be abused and misinterpreted. It is frequently a most difficult matter to draw any line of demarcation between occasions when the indications of a test are of significance in the use to which the material is ultimately to be put, and when they are not. It may be a relatively simple matter to discriminate between extremes, but in the broad borderline between the two, interpretation becomes a matter for expert handling.

Furthermore, in this new field, a considerable period of development may yet be necessary to establish the meaning of any particular set of observations. In this respect all new methods of testing have required a period of trial, and reliable interpretation has emerged only after considerable investigation and use.

Supersonic testing is but one of the many metallurgical tests which need relating to service behaviour before their significance can be established. Amongst these are magnetic crack detecting, radiography, fracture and deep-etching tests. Indeed, none of the more or less standard methods of examination which have been very thoroughly investigated and almost universally practised, should be used without due cognizance being taken of their limitations.

Accordingly, supersonic examination should be regarded primarily as a new instrument of investigation, capable of giving information about the internal character of masses of steel, which cannot at present be obtained by alternative means. It does not, of itself, distinguish the bearing which the observations may have on the suitability of a material for any specific purpose.

DISCUSSION.

(Figs. D to H = Plates XXXA. and XXXB.)

In the absence of Mr. D. O. Sproule, Mr. A. C. Rankin presented Section 2 of the paper, and Section 3 was presented by Dr. C. H. Desch, F.R.S., on behalf of Mr. W. J. Dawson.

Mr. L. Rotherham (Messrs. Thos. Firth and John Brown, Ltd.): I do not wish to add anything to the written matter in the paper in so far as it deals with large masses of steel, but I should like to add a little emphasis to Dr. Desch's remarks on the damping-capacity measurements, partly because I do not think that the importance of the work is fully realized. Damping-capacity measurements of the kind that Dr. Frommer started are, I think, more selective if they are properly interpreted than are the supersonic observations. The contributions to damping of elastic phenomena and the effects of heat-treatment, plastic phenomena, and flaws can be distinguished to an extent; but that is not possible with the supersonic apparatus and, in fact, the total scattering of energy is not measured, but only that energy which is scattered in a particular direction. That, I think, is *the* serious limitation at the moment on interpreting the results, and it is the reason why the contributors to Section 3 of the paper tend to be guarded in their statements as to the information which can be obtained by supersonic testing.

Both Mr. Rankin and Dr. Desch, in presenting the paper, referred to the attenuation of supersonic waves in metals, and that is a line of investigation which we are studying. I cannot say that we have had any success at the moment, but it seems to be fairly obvious that when dealing with segregates and inclusions, for example, they present a different area to the supersonic beam

according to the direction in which it is passing through the material; the scattering will be different, and consequently so will the attenuation of the waves, according to the direction in which they are passed through the steel. We all know that the mechanical properties are themselves dependent on the direction in which the test-piece is cut, and I am hoping that by a more intensive study we shall be able to obtain some correlation between a quantitative measurement with the supersonic apparatus (as opposed to the qualitative which we have at the moment) and mechanical test figures; this will help us a good deal in interpreting the results.

I had hoped at one time that we could single out the effects of damping capacity and scattering but, at the moment at any rate, that seems to be too difficult for theoretical interpretation, and we shall have to be content with the experimental approach.

I mention this not because we have not so far obtained any success, but in the hope that other people who may have done something similar, or perhaps the representatives of Messrs. Henry Hughes and Son, Ltd., may be able to give us some advice which they feel would be helpful.

Mr. H. Nicholson (English Steel Corporation, Ltd.): Some of the advantages and limitations of supersonic testing have been outlined in the paper and I am sure that the matter made available therein will prove to be of considerable value to those considering the application of supersonic principles to their testing problems.

Complementary to those examples given in the paper, and with particular reference to the larger masses of steel, it might be mentioned that subsequent work has been of a confirmatory nature and has resulted in quite definite responses being obtained from hair-line cracks, from large-type inclusions, and from internal-shrinkage cavities.

I should like to emphasize, however, that, in general, only when the results have been supported by other methods of testing, has a definite decision been reached with regard to the suitability of an item for service. I feel that Dr. Desch has quite correctly emphasized the limitations of the supersonic instrument as an all-purpose method of inspection. In its present stage of development it is proving most useful in the investigation of internal soundness in steel forgings, castings, &c., but it would seem that the stage has not quite been reached when the supersonic test can be used and universally accepted as a specified method of testing.

Professor P. G. Bastien (Messrs. Schneider & Cie., Paris): I have read the paper with great interest, and desire to congratulate warmly Dr. Desch and his co-authors on having elaborated a method which permits the detection of defects in components at a considerable distance from the surface, *i.e.*, in cases which arise frequently when magnetic and fluorescence methods cannot be used.

Although submarine echo-sounding by means of supersonic waves owes much to the work of the French physicist Langevin, this method has not been applied to metal components in France, and therefore there are only a few questions which I can put to the authors. In the case of very large components, such as the rotors of powerful turbo-alternators, the simultaneous propagation of longitudinal and transverse vibrations ought to be easy; is a satisfactory elimination of the transverse waves always possible? Further, would the supersonic method, if applied alone, be sufficient to characterize hair-line cracks or other discontinuities in a large forging, and be a suitable basis for the acceptance or rejection of the piece in question? Put in another way, it is possible with components of small or medium thickness to explore by X-rays the doubtful regions to which the supersonic method has called attention. In view of the fact that this is not possible in the case of large components it would be of interest to learn the authors' opinion on the applicability of the supersonic method by itself.

Mr. N. S. Brommelle (British Aluminium Co., Ltd., Gerrards Cross, Bucks): My interests lie in the aluminium industry and not the steel industry, but I take it that many of the properties of the supersonic flaw detector are applicable to aluminium problems just as much as to steel problems. I should like to ask whether the supersonic method could be used for the detection of pin-holing in aluminium blocks, castings, &c., as an assessment of porosity, and exactly how it would be used for that purpose; would it be done by attenuation or would you use a very high frequency and detect, as it were, individual pin-holes in a given region? I should like to know whether the methods of attenuation have actually been worked out for that purpose.

Secondly, I noticed in the paper that the use of plastics and plasticine is recommended for interposing between the test-probes and rather irregular or curved surfaces. Has that been developed? It seems to me that it would greatly facilitate the investigation of curved and very irregular surfaces.

One point which has not been fully dealt with in the paper is the effect the supersonic wave has on metallic inclusions—such as segregates of microconstituents in aluminium, for example, $CuAl_2$, and iron–silicon-rich phases. Is it possible to detect inverse segregation of the type that frequently occurs at the surface of aluminium rolling slabs? In cases where the segregate of iron–silicon-rich metal has to be removed by

scalping, it would be interesting to know whether the detector could be used to find out whether the scalping has been carried out satisfactorily.

Mr. E. G. STANFORD (Aluminium Laboratories, Limited, Banbury): In the discussion of this excellent paper I thought that it would be of interest to review, briefly, some of the work which has been done at Aluminium Laboratories, Limited, on the application of the supersonic flaw detector to the detection of internal defects in light-alloy extrusions and cast billets. In the course of this, I may perhaps provide the answer to some of the questions which were raised by Mr. Brommelle.

The conclusions drawn in the paper from the work which has been carried out on the inspection of steels indicate to me that it is considerably more difficult to evaluate the characteristics of internal defects in steels than it is in light alloys and, while the supersonic test has been established on a routine basis in the aluminium industry, using semi-skilled labour for its operation, this has not been possible in the iron and steel industry.

For the routine examination of extruded rectangular sections we have mounted the apparatus behind a line of rollers on which the sections move forward; the operator stands opposite the cathode-ray tube and holds the crystal probes on to the surface of the section. For the examination of extruded cylindrical bar and cast billets, the bar, or billet, is mounted in a cradle and arranged to rotate about its own axis in addition to travelling forward on the conveyor.

Extruded surfaces require no preparation prior to the examination. Cast surfaces are a little more difficult and often require machining or grinding. The surface transmitting medium used is a solution of lanolin in white spirit; this was chosen because it is normal practice to dispatch light-alloy, semi-finished components with a protective coating of lanolin.

A type of crack which is sometimes found in rectangular spar sections is shown in Fig. D,

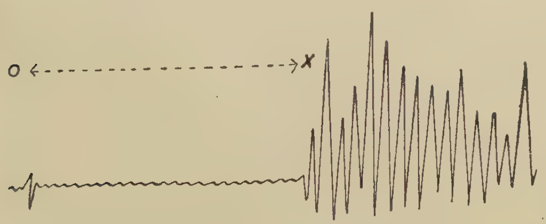


FIG. A.—The Form of the Cathode-Ray Trace which Indicated the Presence of the Crack Shown in Fig. D.

and the form of the cathode-ray trace which indicated the presence of this crack is shown in Fig. A. It will be noted that the bottom echo appears to have moved forward bodily along the trace and it has been found, in the case of rectangular sections, that whenever such an indication appears on the screen it denotes the presence of a large defect, as, of course, might be expected.

In rectangular extruded sections we have found from time to time that we detect minute defects which are smaller than the wavelength of the transmitted pulse. Fig. E shows such a defect which, from the photomicrograph shown in Fig. F, was found to be of the order of 0·03 in. wide (in the direction of the cross-section). The frequency of the supersonic pulse used was $2\frac{1}{2}$ Mc./sec., corresponding to a wavelength of the order of 0·1 in. Fig. B is a diagram of the

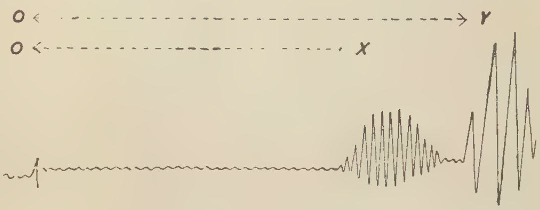


FIG. B.—The Form of the Cathode-Ray Trace which Indicated the Presence of the Defect Shown in Fig. E.

trace which indicated the presence of this defect and it is seen that the reflection from it was of higher frequency than the bottom echo; thus we assume—and I should like to have the authors' opinion on this matter—that such defects are detected by the reflection of the higher harmonics of the supersonic note sent out by the transmitter.

From the inspection of extruded cylindrical bar it is considerably more difficult than with rectangular sections to form an idea of the size and type of any defect which may be present within the bar. This is probably due to the fact that only a small proportion of the total amount of energy emitted by the transmitter reaches the receiver and, in my opinion, it would be worth while experimenting with the design of the transceiver unit, for I believe that better results would be obtained by the use of cylindrically curved crystals fitted to cylindrically curved shoes.

The question of the detection of segregation has been raised. Dr. H. K. Hardy has been working with us on the metallurgical side and in testing specimens provided by him we have only been able to detect the presence of segregates of the $MnAl_6$ type, using the $2\frac{1}{2}$-Mc./sec. pulse. This type of segregate contains minute cracks, but since in the samples tested the volume of segregation was composed of a large number of minute particles, the largest of which was of the order of 0·001 in. in dia., it is most unlikely that these cracks provided the means of detection. The other alternative is that detection was effected by reflection from the boundaries of the segregate; if such was the case, we are immediately confronted by the need for providing a reason for

our inability to detect other types of segregation, such as, for example, eutectic segregation which does not contain cracks. Furthermore it seems reasonable to expect that, within the volume of the segregation, scattering, rather than reflection, of the supersonic beam would take place. We cannot explain why we manage to detect this $MnAl_6$ type of segregate and I should appreciate the opinions of the authors on this subject.

In the examination of cast billets we have, in some cases, experienced trouble owing to porosity, but this has been overcome by the use of filters and we now feel confident that by searching from the cylindrical surface of the billets we can detect the presence of any internal cracks. We should, naturally, prefer to search from the sawn ends of the billets, but when we do this we get rather peculiar effects. Our experimental work was carried out on billets 16 in. in dia., cast by the continuous casting process; the orientation of the grains in these billets is shown in Fig. G, which is a photograph of an etched longitudinal section of a billet specially prepared so as to exaggerate the grain orientation for illustration purposes. Fig. C represents a billet, and we have found that

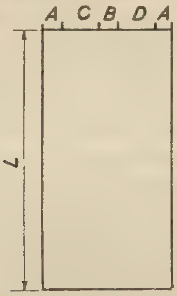


Fig. C.—Diagram of a Billet, showing positions used for searching.

when the length (L) of the billet is *greater than about* 20 *in.*, the following results are obtained :

(1) With the transceiver unit placed at positions A a bottom echo is obtained.

(2) With the transceiver unit placed at position B a bottom echo is obtained.

(3) With the transceiver unit placed at either position C or position D, no bottom echo is obtained; but with the transmitter placed at C and the receiver at D, a bottom echo is obtained.

From these results it would appear that the grain orientation influences the direction of the path of the supersonic beam and that, in the positions C and D, the beam is refracted. It would be interesting to know whether the authors have had similar experiences and what interpretation they would offer.

Occasionally we come across cracking in thin extruded sections and lamination in sheet, the detection of which is impossible using the present apparatus. It would be useful, therefore, if the difficulty of searching materials of thickness less than $\frac{1}{2}$ in. could be overcome. The claim is made * that the Sperry equipment, manufactured in America, is capable of detecting cracks within the first $\frac{1}{2}$ in. of a material, though the method of achieving this is not described and, so far, we have no evidence upon which to judge the extent of its success. In addition to this feature it is also stated that the Sperry equipment may be used for grain-size determinations. I do not know how far the justification for this latter claim is valid, but I think that it warrants investigations, since an easy means of estimating grain-size would be extremely useful; I am thinking in particular of the determination of grain-size in creep-test specimens where a record of such details is of importance.

The authors of this paper have quite rightly stressed the fact that the results which have so far been obtained from the inspection of steel must be regarded with a certain amount of reserve and that, until sufficient information has been gathered from a wide field of practical experience, it would be dangerous to lay down hard and fast rules with respect to the quality of steel components. In this connection I think that we can perhaps be of assistance in establishing the required background of knowledge, for we sometimes experience trouble with cracking in steel rolls and, as a result of this, we have carried out a survey of rolls in stock. We have found that some of these rolls contain internal cracks well down below the surface and have plotted the position and configuration of these cracks so that after periods of service we can trace whether or not the cracks increase in size. It should be mentioned that most of the rolls tested have had considerable periods of time in service. Naturally we have not progressed very far with this investigation yet and, at this stage, we should hesitate to make any generalizations, but we have noticed that steel rolls, which give a picture on the cathode-ray tube similar to that given by a porous aluminium-alloy billet (this picture is characterized by a poor bottom echo), show a tendency towards developing surface cracking in the form of a mosaic pattern; furthermore, in the past, these particular rolls have needed regrinding after relatively short periods in service. If the results of our investigations would be of interest to members of the iron and steel industry, we should be pleased to make them available.

There is one other matter which I should like to mention in conclusion. Personnel engaged on roll grinding are concerned not so much with the

* F. A. Firestone, *Metal Progress*, 1945, vol. 48, p. 505.

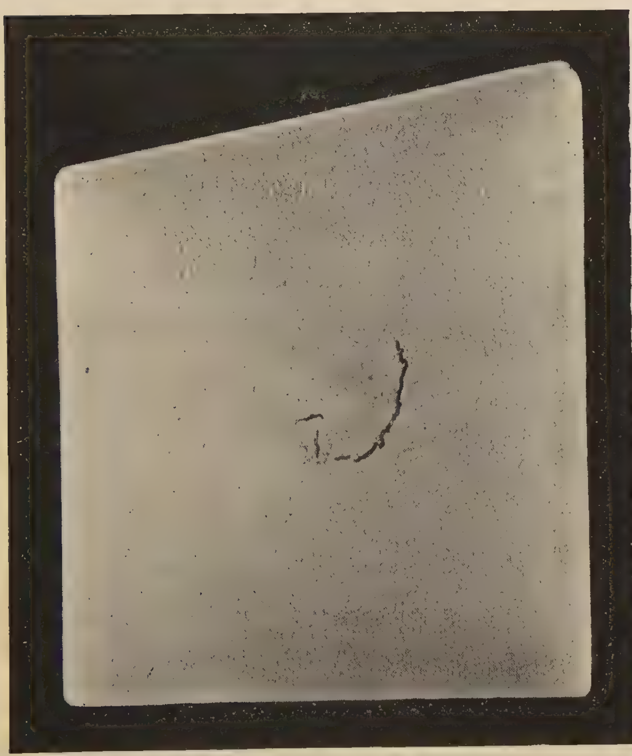


FIG. D.—Type of Crack Sometimes Found in Rectangular Spar Sections. (*See* E. G. Stanford's contribution.)

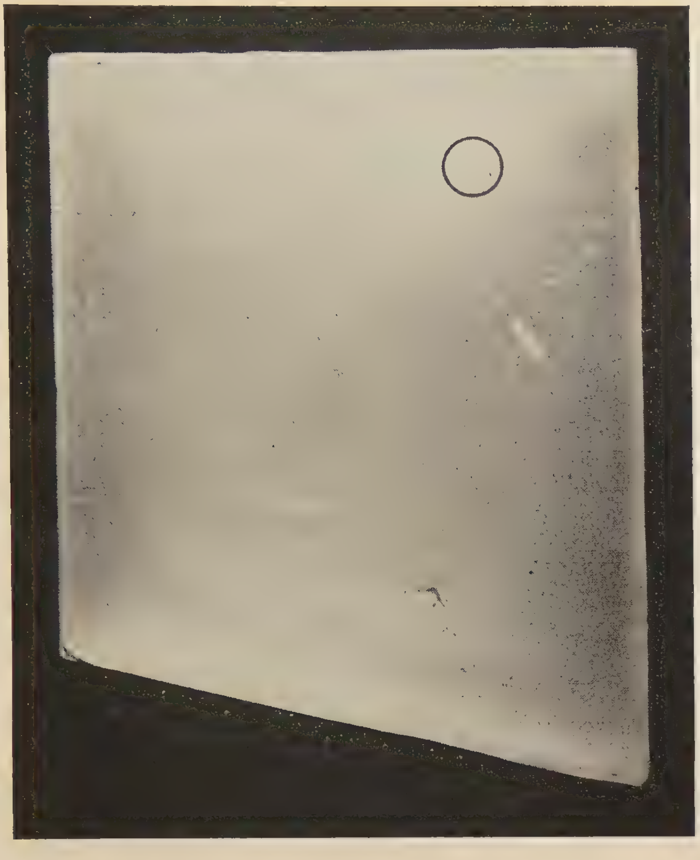


FIG. E.—Minute Defect Found in a Rectangular Spar Section; the dimensions of the defect were smaller than the wavelength of the supersonic pulse. (*See* E. G. Stanford's contribution.)

FIG. F.—Photomicrograph of the Defect Shown in Fig. E. × 100. (*See* E. G. Stanford's contribution.)

FIG. G.—Grain Orientation in a Longitudinal Section of a Billet Cast by the Continuous Casting Process. (*See* E. G. Stanford's contribution.)

FIG. H(*a*).

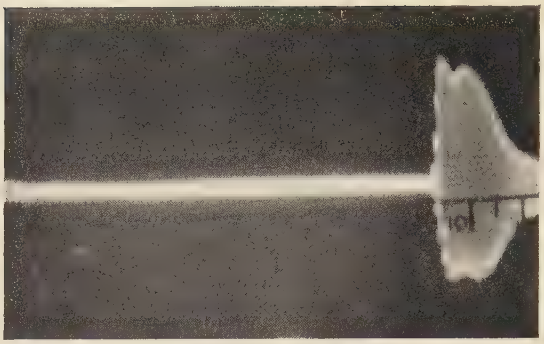


FIG. H(*b*).

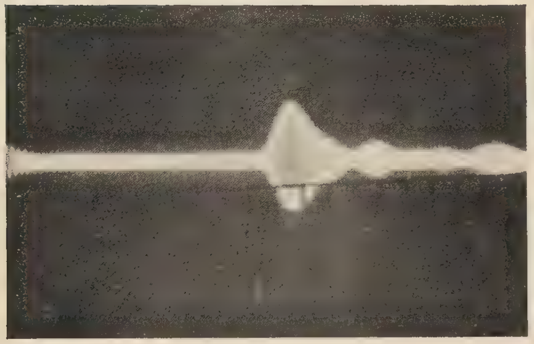


FIG. H(*c*).

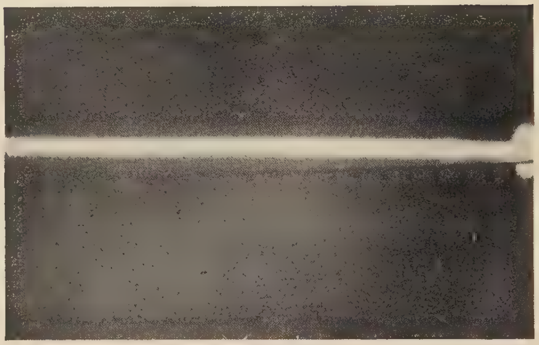


FIG. H(*d*).

FIG. H.—Oscillograph Traces Obtained from a 3-in. Rolled Billet, showing the effect of (*a*) smooth surface, and (*b*) rough, scaled surface; (*c*) shows the echo from a small central segregation, and (*d*) the trace when no flaw is present. (*See* A. C. Rankin's contribution.)

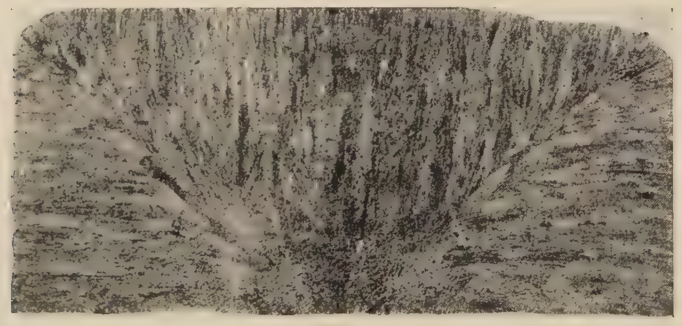


FIG. I.—Portion of a Cross-Section of the Ingot (Macro-Etched). (*See* W. C. Heselwood's reply.)

detection of surface cracks as with their removal; thus it would be an advantage to these people if some means could be devised whereby the depth of penetration of a surface crack into a roll could be estimated. It is not an uncommon experience to find that, after two or three weeks of work have been spent on grinding out surface cracks, the roll diameter has decreased beyond the permissible minimum before the cracks have been removed. This is a problem on which we are working at the moment, but so far we have achieved no success.

Mr. D. A. Oliver (William Jessop & Sons, Ltd.): I should like first of all to pay a tribute to the authors of this magnificent co-operative work, because I think that it gives a most valuable preliminary survey. The authors of the different sections of the paper are careful throughout not to claim finality, which is important, because we appear to be on the verge of wider developments and at the present stage excessive claims should not be made. The whole venture owes a great deal to Dr. Desch, who sponsored the idea when it looked a hopeless quest, and much credit is due to him for his support.

Fig. 3 worried me a little because the beam is drawn as a series of diverging lines, and I should like to explain how I understand the beam occurs. If we have a point source, such as a small piston situated in an infinite baffle and radiating into a uniform medium, then, provided that the source is small compared with the wavelength, λ, at any frequency, the radial intensity pattern is a hemisphere or, as we are drawing it in one diametral plane, it is a semi-circle (Fig. J (*a*)). Now, we know

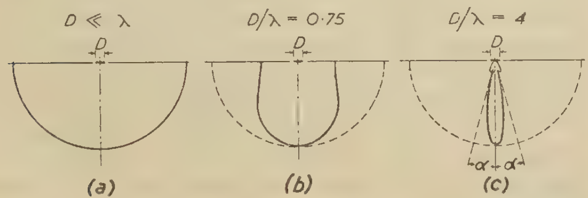


Fig. J.—Propagation of Supersonic Beams.

that the supersonic beam is certainly not as divergent as this, and the basic explanation is as follows: As the wavelength is reduced inversely as the frequency, a finite source becomes progressively large compared with the wavelength, and focusing occurs, owing to interference by path-length differences to different areas of the source from a given external point. Thus in Fig. J (*b*) we have a case where $D/\lambda = 0{\cdot}75$ and in Fig. J (*c*) where $D/\lambda = 4$, where D = diameter of source. However, in the paper we learn that for the probes used (and assuming that the effective source diameter is equal to the diameter of the crystal) we might reasonably expect much sharper focusing than is shown in Fig. J (*c*), as D/λ in this case = 10. When searching for defects in steel blocks it is the sharpness or bluntness of this intensity petal that determines the discrimination.

It would also be interesting to learn from Mr. Sproule whether the angle θ in equation (1) in the paper is likely to be equal to the angle α in Fig. J (*c*).

There is one other very important point about this method of testing at the moment. My colleague, Mr. G. T. Harris, who is a part author of Section 3 of the paper and who has worked on this subject with me from the beginning, would doubtless agree that the only real successes which we have had have been obtained on really simple forms of test-piece. We have had occasion to examine very meticulously some forged discs for gas turbines and jet engines, and we were particularly anxious to check the soundness of the centre of the forging. Two faces of a fairly thick disc, 4 or 5 in. thick, were carefully machined and explored over the whole central region with the probes. Many hundreds of forgings in all were inspected. The supersonic test proved to be an exceedingly valuable method of inspection. We were not looking for, nor did we find, hair-line cracks, because the steel was austenitic. We did, however, locate a measure of axial porosity, and the energy absorption of the very slight looseness in the structure was broadly capable of calibration. We were able to build up a background and interpret the results and correlate them approximately with mechanical tests.

Taking a view into the future, I think we probably want sharper and more powerful beams from smaller sources, and we definitely want the background fluctuations reduced to a minimum. Thus the reflections can be made more accurate and more certain as a method of detailed fault location.

Dr. M. J. N. Pourbaix (Association des Industriels de Belgique A.I.B.): Professor G. A. Homès of Mons and M. Y. Verwilst of Brussels have asked me to mention that they have developed a method for supersonic testing of materials, with the collaboration of the "Ateliers de Constructions électriques de Charleroi A.C.E.C."

The main part of this work was done in Belgium during the enemy occupation and had to be preserved from German curiosity. The conditions under which the work was done were therefore very difficult, and the results have not the scale of those recorded in this magnificent paper, but these Belgian workers did the best they could.

The apparatus consists of two parts:

(1) A transportable metal box, with a volume of about 2 cu. ft. and a weight of 30 lb., which contains a high-frequency generator, a receiver, and any accessories.

(2) Two elastic sounders which secure acoustic contact with the material.

The intensity of the transmitted or reflected supersonic waves may be estimated with a milliammeter or with a loud-speaker. It is not necessary to immerse or to smooth the surface. The elastic sounders make possible the examination of materials with a rough surface and may be found useful for this purpose.

The apparatus was used by those who devised it for detecting defects in different materials in sheet, strips, and bars. They have examined objects in metal, porcelain, plastics, and wood.

Mr. W. R. Yates (Messrs. Hadfields, Ltd., Sheffield): I should like to reply to the questions raised by operators who have had experience with the examination of light alloys. With regard to the use of plastic adapters for regular curved surfaces, a technique has been devised using a warmed sheet of Perspex which is moulded to the contour of the surface under pressure. The coupling medium, used between the flat probe heads and the Perspex and between the Perspex and the surface of the specimen, is light machine oil.

Mr. Stanford referred especially to the use of the supersonic method for the examination of light-alloy castings, whereas in the steel industry much of our work has been on rolled and forged material. One result of the working of the steel is that defects often lie in one plane, hence, examination is usually made from two directions at right angles. The principal types of defect occurring in this class of material are hair-line cracks and segregation.

The sensitivity of the instrument is to some extent dependent on the surface of the material and, where possible, specimens are machined and then ground before examination. It sometimes occurs that preparation of the surface is not practicable, as, for example, with large forgings in the works; in this case the use of a filter of 2½ Mc./sec. has been found to improve the sensitivity of the instrument. In our early work a filter tuned to the frequency of 1¼ Mc./sec., which was the natural frequency of the 30° wedges, was used. This frequency is also that of the transverse vibrations arising from transmission along the surface, hence the increased amplitude of the echoes was accompanied by increase of amplitude from the transverse vibrations. The use of the higher frequency filters reduces transverse disturbance whilst increasing the sensitivity of the instrument.

Mr. W. C. Heselwood (The United Steel Companies, Ltd.): The most successful application of supersonic testing has, I think, been on hair-line cracks, and it is right that we should recognize, as Dr. Desch has pointed out, that this was the first objective of the apparatus, and that objective has been achieved. It has also been found that other useful applications are possible. We have only met one case (referred to in the paper) where hair-line cracks known to be present by sectioning and magnetic etching have not been revealed by the supersonic methods; there was a full explanation for this particular result, in that they were few in number and very small indeed, smaller, in fact, than the wavelengths which we were using.

In my view the two chief limitations of the present equipment are :

(1) Its relative lack of success in the examination of cast steel, including ingots; the supersonic energy seems to be dispersed by the inherent " looseness " of the cast structure.

(2) Its inability to detect by reflection defects less than about 0·5 in. from the surface.

With regard to the portability of the equipment, it is right to say that it is at any rate transportable, if not easily portable. The later forms are very much lighter than the earlier ones.

There is reference in the paper to the examination of thin plate by a transmission method, where the thickness of the plate is too small to be examined by reflection. In that case one can look for major discontinuities by putting the transmitter on one side and the receiver on the other and using a shadow method. For the examination of plates up to 12 ft. wide, we have made up a pair of light-alloy tongs of " sugar-tongs " type, containing a pair of supersonic probe leads 10 ft. long and capable of working across a sheet to a distance of 6½ ft. from either side. Water plus a little wetting agent was used as the intermediate film between the probes and the surface, a device being incorporated in the tongs which enabled a little of this liquid to be squirted on to the place where the tongs were about to close. The tests are still in the experimental stage, but the method has been found to work fairly satisfactorily.

Mr. A. C. Rankin (Messrs. Henry Hughes and Son, Ltd.): I should like to take part in the discussion on this paper, which may well form the foundation stone of a non-destructive testing method equally as important as radiography. In particular I want to discuss the more recent work which we at Messrs. Henry Hughes have done in conjunction with the steel industry on the problem of surface preparation, a problem which has been emphasized throughout the whole of this excellent paper. In Section 2 Mr. Sproule mentioned that waves with a frequency of 1¼ Mc./sec. (which, as Mr. Yates has said, seems to be the natural frequency of the wedge transmitter–receiver system) enables testing to be done

through the normal black surface of the rolled material, and this has been very successful. It has been applied in practice in a steelworks in England where production testing of billets and blooms has been established for some considerable time. An accurate logbook of the results has been kept which, coupled with check destructive tests, shows clearly their fidelity.

I should like to give one warning on this subject: Using the 1¼-Mc./sec. filter, there is some tendency for low-frequency transverse surface waves to creep through the amplifier and, as a result, not only do we find echoes coming from defects and the bottom boundary but, in addition, we find early disturbances due to these transverse waves. These can be readily differentiated by an experienced operator, but nevertheless it is a point which I should like to emphasize.

Mr. Yates also mentioned some of the work which we have done with two 2½-Mc./sec. filters in penetrating rough surfaces. We have seen from Figs. 15 (iv) and (v) of the paper that the amplitudes of signal are so small as to be virtually useless at 2¼ Mc./sec. with the normal arrangement. The latest technique evolved is really one which depends upon a purely electrical dodge, which I shall presently explain. The term " filter " is rather unfortunate because, not only does it act in the amplifier as a filter to prevent these transverse waves but, in addition, it acts as a resonant circuit in the amplifier side and, in consequence, we get increased gain. On rough surfaces this increased gain is most useful although, if not completely understood, it may also lead to misinterpretation. Some experimental work has shown that by utilizing resonant circuits in conjunction with both transmitter and the receiver, the high gain is most useful. This has been the subject of investigation primarily by ourselves but, lately, also by the group of investigators responsible for Section 3 of the paper.

Figs. H (*a*) and (*b*) show the comparison in the amplitudes obtained on a 3-in. rolled billet for the bottom echo using (*a*) a smooth surface and (*b*) a rough surface, again from the bottom of the same sample, and using the double-filter technique. It is obvious that these are comparable.

There are again some warnings which should be given about this new system. It is not yet quite certain whether this method is going to be the final solution or not. So far, the work which we have done on rolled sections for pipe, central segregations, and so on, has been successful, but there is the possibility that the drawing out of the wave train, which occurs because of the use of these tuned circuits, is going to create difficulty in giving a sharply defined echo from flaws, and it may be necessary to increase the power output of the transmitter and retain the normal concept of a flat amplifier, as is used normally on smooth surfaces.

Fig. H (*c*) shows the echo from a small central segregation in a 3-in. billet of the same type as Figs. H (*a*) and (*b*), while Fig. H (*d*) illustrates the equivalent oscillograph trace when no flaw is present. In explanation, these last two figures correspond to the case when the wedges are set at such a distance apart that the area of maximum sensitivity corresponds to the central axis of the billet.

I should also like to mention a few of our own experiences in testing. We, as makers of the instrument, have tried to co-operate with the industry and we always want to understand clearly what it is that is required. The question of cast material has been raised; in our experiences with the testing of cast materials, what strikes us is that it is not so much a limitation of the principle of supersonic testing, as a limitation of the metallurgical practice. In any cast material, we very rarely find complete homogeneity and, therefore, we have to learn how to ignore things which can be tolerated and how to find others which cannot be tolerated. Often it is like looking for a tree in the middle of a wood and, as such, it brings out the fact that we cannot violate physical principles in order to achieve our results. The work on castings, of course, is still going on.

I should also like to make a few points on the system of the Sperry Reflectoscope which Dr. Desch has mentioned in Section 1 of the paper. There have been some recent publications on this, including one,* published in *Iron Age*, from which it is clear that the Americans have had precisely the same difficulties as we have had. They do not seem to have got over the difficulty of requiring a smooth surface, and the amount of smoothness necessary is very much more than is practical in most cases where the cheaper types of steel are concerned. Moreover, in this American paper, which is fairly recent, it is stated that testing could not be carried out under a thickness of 1 in. with the equipment in question but that it was possible using specialized techniques. In another paper,† there is also reference to this, and it is stated to be due to the fact that the transmitted pulse has barely left the transmitter before it is received; in other words, the two mix and an interference pattern is obtained. With regard to the single transceiver, which has been suggested and which is used in the Sperry equipment, the paper published in *Iron Age* states that in the case of the sheared ends of the billets no bottom echo can be obtained and, also, that the echo is very much dependent on flaw orientation. In this respect, while no doubt a

* Russell and Pellet, *Iron Age*, 1946, vol. 157, No. 5, p. 38.

† de Lano, jun., *Electronics*, 1946, January, p. 132.

single transceiver would be very useful for rapid testing, the double transmitter and receiver system has many points in its favour and does not compare unfavourably with the single transceiver in most respects.

The question of grain-size measurements has also been raised and is worth some consideration. Some work has been reported by Firestone in America. The frequency used was 5 Mc./sec. and while, in the case of the experiments described by Firestone, a block of brass was cut in strips and heat-treated to give relatively large differences in grain-size, the point that should be remembered is this: In order to get interference by grain boundaries, normally it is necessary to utilize a relatively high frequency, and in so doing the wavelength is shortened so much that one also gets absorption by the general inherent inclusion fields; and, therefore, when successive echoes are being measured—in other words, the attenuation of the waves—two factors have to be separated: Firstly, the effect of grain-size and, secondly, that of inclusion distribution and size. In this respect, I should like to point out that in cases where there is not a large variation in grain-size, but there is considerable variation in cleanliness, it would be very difficult to obtain any accuracy with the method. The idea, nevertheless, is worthy of further investigation, not only as a measure of grain-size, but also possibly as a measure of cleanliness.

Finally, it may be of interest to record that the method has also been used successfully to detect longitudinal and transverse cracks in compressed carbon.

In conclusion, I should like to associate with my remarks my colleague, Mr. H. M. Jefferys, who throughout the complete history of flaw detection has done much to further the practical testing techniques with which this discussion is concerned.

CORRESPONDENCE.

Mr. A. G. Warren (Armament Research Department, Woolwich) wrote: The application of supersonics to non-destructive testing is one of those obvious lines of work which often demand extensive research before a practical technique is achieved. It is seen from the present paper that, in this country, considerable progress has been attained in the development of the reflection method. It appears that in Germany effort has been mainly applied to transmission methods. It is perhaps not an unmixed evil that workers in the two countries have been unaware of each other's failures. On p. 320 P of the present paper it is indicated that early experiments with the transmission method were unsuccessful in this country in detecting hair-line cracks and so effort was applied to the reflection method. It appears that in the early German experiments more promising results were obtained from transmission methods. Pohlman claims that his method is very sensitive in detecting hair-line cracks and he substantiates his claims with photographs which are convincing. There is no doubt that his detector is very attractive and, in suitable cases, gives indications which are relatively easy to interpret.

Of course, as is remarked on p. 320 P of the paper, the power required by the reflection method is much less than that consumed in Pohlman's apparatus. But, as at the present time only a small fraction of the energy available in the reflection apparatus is utilized, it is hardly fair, without further examination, to claim power economy as an advantage of the reflection method. If Messrs. Hughes were to transmit an appreciable fraction of the sonic energy available into the material under examination they might, with their present detector, be embarrassed by the intensity of the reflected signals. Referring to Fig. 2 (*a*), the quartz is free to transmit along two parallel paths, one into the steel, the other into air. The acoustic impedance of steel is nearly 100,000 times that of air and at the natural frequency of the crystal only a small fraction of the energy available is transmitted into the steel. If more energy is required wave technique can be used, and transmission in any but the desired direction practically inhibited. It is as well to forget, temporarily at any rate, that the quartz has a natural frequency. The reduction of total impedance brought about by operating at the resonant frequency of what should be but a small fraction of the complete oscillating system is negligible.

On the Continent much use has been made of ultrasonic lenses and much attention has been given to their development. In this connection a paper by Ernst (*see* reference 8 to Section 1 of the paper) contains some useful information. I do not accept his deductions from various mathematical expressions without reserve. Too frequently Rayleigh's equations are misinterpreted; consider, for instance, equation (8) on p. 325 P, here called Wood's equation, and referred to by Ernst as "Boyle and Rawlinson's fundamental formula." (Rayleigh made no claim to originality when he gave the equation not less than 50 years ago.) It is a well-known equation in wave transmission past a junction when losses are neglected. If the

equation be applied in the way it is here applied to electric waves along wires, one arrives at the conclusion that the transmission of electric power over any but the shortest distances is a practical impossibility. The assumption that has been made is of course that the reflected energy does not react upon the source. The equation may therefore be applied with some approximation to accuracy to a hair-line crack in a metal at a depth several times the beam width. But it must not be applied to the transference of energy from a transmitter to a mass of metal through a thin film of oil. If the thickness of the oil film is very small compared with the beam width, then, on the basic assumptions made in deriving equation (8), the transmitted beam must be equal to the incident beam and the effective reflection zero.

The fact that the efficiency of transmission is not 100% must not be expected to be explained by the inapplicable equation (8). If it has not already been done it should not be difficult to work out the applicable equation. Relevant factors are the relative acoustic impedances, diffraction, and dissipation.

Other things being equal, a coupling liquid of high acoustic impedance is likely to be more efficient than one of low acoustic impedance. But it is possible that a liquid may be found which has a particularly low dissipation and which may be more efficient than one having a higher acoustic impedance.

To some extent I think the particular fields of application of the reflection and transmission methods will be found to be complementary. The inevitable competition of the two methods is likely to be mutually beneficial.

Dr. H. O'Neill (London, Midland and Scottish Railway Company, Derby) wrote: British railway research workers are indebted to Dr. Desch and Mr. Sproule for describing a piece of apparatus which is successful in detecting flaws in steel. Its application extends beyond the search for hair-line cracks. In 1937 the L.M.S. Research Department was set the task of detecting transverse fatigue fissures which might be present in railway-carriage axles at a wheel-seat position *within* the hub of press-fitted wheels. Such flaws might develop through alternating and combined stresses at the fretted portions of the ends of the wheel seats. The detection of these cracks without pressing-off the wheels is very difficult, yet their presence might eventually lead to an axle fracture which would have serious consequences. Team-work was instituted,* and in a report in 1938 the writer showed that whilst electrical conductivity methods yielded results, the employment of supersonic waves should also be considered. At that time the methods of Sokoloff were the only ones which had been heard of, and they did not offer any promise of easy application. A mechanical deflection test † was finally adopted with success, but the advent of the apparatus described by Mr. Sproule opened up new possibilities. The L.M.S. Engineering Research Section have adapted this equipment to the testing of wheel and axle assemblies, and the procedure is now being introduced as a routine method of works inspection.‡ The two probes were applied to the machined end-faces of the axle journals and an echo was received from the opposite end. If one or more wheel-seat transverse fatigue flaws were present in the axle, however, they provided a separate indication on the cathode-ray oscillograph. The wheels were then pressed off and a further examination was made.

Hair-line cracks in railway tyres might cause trouble if undetected. Damping-capacity methods have been considered for non-destructive testing, but finally without enthusiasm. "Super wheel-tapping" by supersonic waves is now looked upon as a more suitable method of examination, and tests have been made on a tyre from a cast which provided examples of hair-line cracks. Application of the probes along the machined flange face of this tyre produced indications of some small internal cracks, and these were later observed when the tyre was sectioned and etched.

As regards the testing of welds, the supersonic method has been tried on a few electric flash butt-welded joints of railway rails. The specimens were about 5 ft. long and the probes were applied to one end. In one case discontinuities were detected and X-ray examination subsequently revealed a weld cavity in the web. When wedge-shaped probes are received it is intended to test the joints from the rail surfaces in the vicinity of the welds. Experience is needed in the application of this new method to the inspection of engineering structures, but its great utility is undoubted.

Mr. A. J. K. Honeyman (Messrs. Colvilles, Ltd., Glasgow) wrote: The authors are to be congratulated on their paper, and not least on their emphasis of the difficulties and limitations attendant on the supersonic-wave methods of detecting defects. While this method may be already established for certain applications, a great deal of work remains to be done before it can be employed as a routine testing procedure when

* H. O'Neill, *Engineering*, 1942, vol. 154, p. 174.
† F. C. Johansen, *Engineering*, 1942, vol. 154, p. 101.
‡ D. W. Spencer, *Journal of the Institution of Locomotive Engineers*, 1945, vol. 35, p. 383.

cost is an important item. Apart from the problems of surface transmission, its usefulness is severely limited by its intensely local action. Dr. Desch mentioned the wheel-tapper. With his apparatus one tap is sufficient to test the whole wheel, whereas the supersonic method applied to the job would be somewhat tedious. Thus the detection of defects, such as lamination in plates and cracks in bars and billets, which may be present anywhere throughout the product of an ingot, becomes a very lengthy and therefore expensive job. On the other hand we have found it very useful in the detection of hair-line cracks in armour plate where a sample is representative of the quality of the whole. It may likewise be useful in the detection of defects such as fish-tail or piping which are confined to a particular portion of the bar. The chief difficulty in testing for pipe and segregation is one of interpretation. As the probe travels along a piped or segregated area the reflection may gradually fade but, owing to minor inclusions of no practical importance, it may not completely disappear. Quantitative interpretation is rendered more difficult by the fact that uniform efficiency of surface contact is not easy to achieve.

Mr. Heselwood has shown how transmission may be applied to plates too thin to permit of reflected waves being picked up, and we have applied this method with the same success. It is, however, not easy to see how this could be conveniently applied to large plates, and in any case the cost would be excessive.

With regard to weld defects it is interesting to note that changes in structure or even the juxtaposition of ferritic steel and austenitic weld metal does not appreciably affect the interpretation of results. Supersonic methods have been applied successfully to testing the efficiency of union between stainless and mild steel in "cladding" processes.

With regard to the work described by my colleague Mr. Glen, it should be noted that these experiments have been carried out on test-samples only. Their application to welded structures is a problem which has not yet been attacked.

AUTHORS' REPLIES.

Dr. Desch replied: Several of the questions raised by speakers in the discussion have been answered by subsequent speakers. It is gratifying to find that a method devised for a specific purpose, the detection of hair-line cracks, is proving to have other applications in both the ferrous and non-ferrous industries. Methods depending on reflection and on absorption have each their own sphere of usefulness. It is evident that by a suitable choice of frequencies, using filters, the range of usefulness can be extended. Means of making acoustic contact with surfaces which have not been ground or polished are capable of further development, and in this connection the diaphragms devised by Professor Homes are likely to prove very valuable. The American devices do not seem to be on the whole as generally adaptable as those worked out so ingeniously by Messrs. Hughes and Son, Ltd., and it is gratifying that in this important field Great Britain has been able to take the lead.

Mr. Sproule wrote in reply: A quantitative investigation of the molecular absorption and the scattering due to crystalline structure, segregation, or other scattering centres of the sort mentioned by Mr. Rotherham, could be carried out using the flaw detector in its present form if used in conjunction with a suitable pulse signal injector. However, the measurements of randomized scattering will be very tedious, and it may be that a comprehensive investigation of this sort will have to await the development of new measuring techniques. We have noted very big differences in the absorption and the scattering which occur in different samples, but it would be dangerous to attempt to use such comparisons in assessing the value of different materials as the flaw detector amplifier in its present form does not give a proportional response over a sufficiently large range. Moreover, measurements of absorption at a frequency of several megacycles per second may not mean very much in connection with a structure that may vibrate in use at a frequency of a few kilocycles per second or less.

With reference to Professor Bastien's question about the applicability of the supersonic method in the case of large components where X-rays cannot be applied or can be applied only with difficulty, there are a number of important cases on record where large components have been tested by the supersonic method and the results have generally been confirmed very satisfactorily by destructive tests. We agree with the note of caution that has been expressed by a number of contributors, and we have seen a number of cases where the flaw detector has shown itself capable of detecting flaws so small that they could have no serious effect on the strength of the sample being tested. In connection with this limitation due to excessive sensitivity on the part of the

flaw detector, we have had a number of cases where a failure would have serious consequences, and we are glad to say the customer and maker have agreed that they would rather reject on the basis of any detectable flaw than take the risk of failure in use.

Mr. Brommelle asks how porosity can be assessed by the supersonic method, and in particular whether this would be tested by its effect on attenuation or by the use of a very high-frequency capable of detecting individual pin-holes in a given region. It is not possible to give a complete and satisfactory reply to this question. The point which is clearest from past experience is that individual pin-holes as small as a millimetre in diameter can be detected by the flaw detector using the $2\frac{1}{2}$-Mc./sec. pulse. The other point which is clear beyond all shadow of doubt is that a general scattering of energy from a region of high porosity can easily be detected in many cases, especially when using a long wave train and the higher frequencies. At the same time it has been found possible in many cases to lower the frequency and reduce the length of the wave train so that it is possible to detect gross flaws in the presence of unavoidable porosity which it is desired to ignore.

It is doubtful that attenuation by itself will give a useful and significant measure of porosity unless other characteristics such as heat-treatment, crystalline structure, &c., are very carefully controlled.

With regard to Mr. Stanford's observation that all echoes are not at the same frequency, and in particular that the echo from the flaw has a higher frequency than the echo from the bottom, I think that this can be explained almost entirely by the fact that the trace in question was obtained by adjusting the probes so that the flaw lay on the axis of both the transmitter and receiver systems, thus giving the maximum intensity of flaw echo. Now, both the transmitter and the receiver have a sharper directional characteristic for the higher frequencies. In addition a small flaw will reflect the higher frequencies more efficiently than it will the lower frequencies. The bottom echo under the conditions assumed above will be from the side lobes of the transmitter and will be picked up by the receiver at an angle such that the receiver has appreciable sensitivity only for the lower frequencies, which therefore predominate.

With regard to the question of reflection from a large number of minute particles, it is essential to realize that if the particles are small in comparison with a wavelength and if the separation between the particles is small as compared with the wavelength, then there will be a reflection from the boundary of the region in which these particles occur, according to the usual laws of reflection, depending on the average elasticity and the average density. In other words, a cloud of particles close together will behave toward the wave in exactly the same way as would a different medium with elastic properties corresponding to the mean properties of the cloud. On the basis of this analysis it would appear that in the case of eutectic segregation which does not contain cracks, the average density and elasticity do not differ sufficiently from the bulk of the metal to give a reflection, whereas in the case of the $MnAl_6$ type of segregate the cracks, rather than the segregate, affect the average elasticity and density sufficiently to give a reflection.

The example of refraction which Mr. Stanford described is very interesting and is probably due to the known fact that the elasticity is a function of crystalline orientation. At any rate, Fig. G shows that the orientation alters considerably, radially across the billet. The simplest substantiation of the explanation would be the careful comparison of the velocity in a direction parallel to the axis through regions at varying distances from the axis. Having made these measurements it would be quite easy to calculate the amount of refraction to be expected due to a temperature gradient and the consequent velocity gradient in the atmosphere, as is done in the case of the well-known mirage.

Mr. Oliver's assumption that the angle θ in equation (1) is the same as a in his Fig. J(*c*) is correct.

Mr. Yates' remarks on the improvement secured by using a $2\frac{1}{2}$-Mc./sec. filter should be expanded in order to include various cases of practical importance. There is no simple rule by which we can specify the best frequency for any given case, but, in general, one should use the highest frequency possible. The principal considerations which call for a reduction in frequency are :

(*a*) Segregation porosity or other randomly distributed small scattering centres which provide reflections capable of obscuring the echo from a larger singularity. In such a case the use of a lower frequency can produce a marked diminution in the scattered energy from the small scattering centres and reveal otherwise undetectable echoes from larger and more important flaws.

(*b*) High attenuation due to molecular absorption or other causes. In general, attenuation is lower for the lower frequencies and in a number of cases of practical importance it has been found desirable to decrease the frequency to $\frac{5}{8}$ Mc./sec., thereby securing a range of several inches or several feet in materials which would give no detectable echo at the higher frequencies.

(*c*) A badly pitted surface (*e.g.*, as cast) or

one with an adherent scale. Here again, the attenuation is less for the lower frequencies.

For these reasons it is sometimes desirable to use lower frequencies in spite of the objectionable surface wave which is then in evidence. It is important to realize that this surface wave can be identified by slowly changing the transmitter–receiver separation, which will cause the disturbance due to surface wave to run across the cathode-ray trace at a speed that is high in comparison with the small movement of a true echo. A little practice will soon enable an observant operator to detect small flaw echoes even in the presence of relatively large surface wave disturbances.

Mr. Heselwood mentions the relative lack of success in the examination of cast steel, including ingots. At the time the results were presented we were beginning to find that the lower frequency, and in particular that of $\frac{5}{8}$ Mc./sec., was rather better in its penetration of the inherent looseness of cast structures and this has since been confirmed on many occasions. We have also carried out some work on the use of high powers in the transmitter, and this has also increased the possibility of success in the case of castings. With regard to the second main limitation referred to by Mr. Heselwood, we are now engaged on research to reduce the permissible distance at which defects can be detected and hope to obtain an improvement of five or ten times in this respect, enabling us to work at distances between 0·1 and 0·05 in.

Mr. Dawson wrote in reply: Replying to Professor P. G. Bastien, regarding the elimination of transverse waves, improvements effected by the introduction of filters in the transmitter and amplifier circuits do lead to the elimination of transverse waves.

The use of plasticine for the examination of rough or curved surfaces was raised by Mr. Brommelle. The experience of the authors has been that plasticine is of great value for use on machined bars of 6 in. in dia. and upwards and also on bars of 3–4 in. in dia. in the forged condition. When the machining of a round bar has left a coarse surface, plasticine helps to fill in the corrugations and eliminates ripples from the trace. The authors have found that plasticine should be used impregnated with oil. It is usually made to adhere to the probe heads, but where the surface is rough it may be rubbed into the surface.

A combination of a supersonic with a radiological examination in the manner indicated by Professor Bastien is at times applied, since the two methods are in a sense complementary. In the case of hair-line cracks the supersonic method is of positive value, whereas the radiological method would be subject to limitations, since anything of the nature of a small crack may not be detected. The X-ray method has been successfully used to define further the nature of doubtful regions revealed by supersonic examination. Dr. O'Neill referred in his written contribution to a case of the complementary use of the two methods applied to the examination of welded joints in rails. I should deprecate in the present stage of development of the method its use as an arbiter of acceptance or rejection and therefore an instrument of inspection. Both methods have their specific uses in defining the character of the interior of a mass of metal, but the question of interpretation in the sense implied involves the consideration of a much wider field of experience, particularly in regard to the bearing a defect may have on the subsequent performance of the article. When the nature of the defects has been defined in a much more precise manner, our knowledge of which is rapidly growing with the aid of these new instruments of non-destructive testing, there still remains the question of the correlation of the results with field experience to define how far any particular type of so-called defect is in effect of practical importance in service. This point has been repeatedly stressed throughout the discussion.

Mr. Warren has raised certain interesting questions relating to the choice of the coupling liquid. It is significant that liquids as widely different as oil, water, and amalgams have been successfully used. Oil has obvious advantages for general use.

In conclusion I should like to thank all the contributors to the section of the paper for which I was responsible for what has been an admirable piece of team-work, and Dr. R. J. Sarjant, O.B.E., and the staff of the Research Department of my Company for their assistance in matters relating to my contribution at a time when I was unable to attend to them myself.

Mr. Heselwood replied: The experience of testing continuously cast light-alloy billets, as described in Figs. C and G, and the related text of Mr. Stanford's useful contribution to the discussion, is particularly interesting. In view of the nature of the grain orientation it seemed important to know whether the same effects are obtained from either end of a billet, and a private communication from Mr. Stanford confirms that they are independent of direction.

The full explanation of this phenomenon is not clear, but it is known that grain orientation can affect the path of a supersonic beam, as was demonstrated in the following early and more simple experience with a steel ingot:

An ingot, approximately 23 in. × $4\frac{3}{4}$ in. square, and tapered in section, was examined along one face, using wedges in line and parallel to the length of the ingot, but at no place could a definite

bottom echo be obtained. It was found, however, that if the supersonic beam was made to enter normally at a position to one side of the longitudinal centre-line of the face, it could be detected emerging from the same face on the other side of the centre-line and the time corresponded to a single thickness of the ingot. When the ingot was cross-sectioned it was found that the columnar crystals reached to the centre (*see* Fig. I, which shows a portion of the cross-section), from which it was concluded that the supersonic beam had suffered successive reflection from the diagonal planes in which these crystals meet. (*See* Fig. K.)

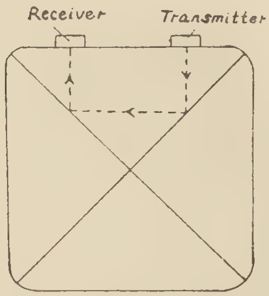


FIG. K.—Suggested Path of Supersonic Beam.

CORRESPONDENCE

on Papers printed in the No. II. Volume of the Journal for 1945.

The following Correspondence has been received on papers included in the Programme of the Annual General Meeting on 1st and 2nd May, 1946, but which, owing to the change of format, have been printed in the No. II. volume of the *Journal* for 1945.

Note on Oxide Systems Pertaining to Steel-Making Furnace Slags. FeO–MnO, FeO–MgO, CaO–MnO, MgO–MnO.

BY A. H. JAY, PH.D., M.SC., F.INST.P., AND K. W. ANDREWS, D.PHIL., B.SC. (CENTRAL RESEARCH DEPARTMENT, THE UNITED STEEL COMPANIES, LTD., STOCKSBRIDGE, NEAR SHEFFIELD).

(*Journal of The Iron and Steel Institute*, 1945, No. II., pp. 15 P–18 P.)

SYNOPSIS.

An X-ray survey has been made of the binary systems FeO–MnO, FeO–MgO, CaO–MnO, and MgO–MnO. All systems show complete solubility at a temperature of 1150° C. The variation of lattice spacings with composition in each system is recorded.

Mr. T. E. ROONEY (National Physical Laboratory, Teddington) wrote: The writer is very interested in the work on the binary systems, particularly the FeO–MnO system. This system is of great importance in the study of inclusions in steel, and the presentation of accurate data on the variation of lattice spacing with composition should prove very useful in this field of research. The indication that in the FeO–MnO system there is 100% solubility at temperatures between 1350° and 1150° C. is a very important fact. The authors are to be congratulated on a very useful piece of work.

Dr. J. WHITE (Sheffield University) and Mr. W. F. FORD (British Refractories Research Association) wrote: For some time past evidence that there is complete solid solubility between FeO and MnO has been accumulating. Whiteley, for instance, to whose paper the authors give a reference, failed to find any evidence of a two-phase region in artificially produced FeO–MnO inclusions in steel. The investigation of this system, as carried out by Hay, Howat, and White, involved melting the experimental mixtures in molybdenum crucibles, and it now seems likely that a change in the metal–oxygen ratio took place owing to reaction with the molybdenum, just as it does when melting is carried out in platinum. By restricting the heat-treatment of their samples to temperatures below those of melting, which enabled them to use iron to support their mixtures, the authors have avoided the possibility of such complications, and their work can be taken as definitely establishing that there is complete solubility, at least at the temperature of their heat-treatments. We have ourselves had confirmation of this since the publication of their results, in that a 35/65 (wt.-% ratio) mixture of FeO and MnO, prepared by heating ferrous oxalate of known iron content with MnO *in vacuo*, was found after 2 hr. at 1300° C. to contain only one cubic phase, of lattice spacing 4·388 kX. units, this value being in close agreement with that derived by interpolation from the authors' results.

The existence of complete solid solubility at high temperatures in this and other binary systems

studied by the authors indicates some interesting possibilities regarding solid solubilities in the systems of higher order formed by these oxides. For example, the addition of MnO to CaO–MgO mixtures should progressively diminish, and ultimately eliminate, the insolubility between CaO and MgO. In a series of experiments carried out after the first intimation of the authors' results (*see* discussion on a paper by Rait and Goldschmidt *), various additions of CaO and MgO, in a constant 50/50 weight ratio, were made to MnO, the maximum addition being such as to give 40% (CaO + MgO) in the ternary mixture. Up to this concentration only one homogeneous cubic phase could be detected by X-rays, so that it is clear that a considerable range of ternary solid solution must exist at high temperatures.

We have also confirmed the authors' finding that there is complete solid solubility between CaO and MnO after firing to 1200° C. for 2 hr. In our case the mixtures were fired as pellets on Armco iron in hydrogen and were slowly cooled in the furnace. Our lattice spacings after this treatment also agreed with those of the authors.

It is as well to emphasize, however, that the above results, like those of the authors, have been obtained after heating to the region of 1200° C. There is evidence that at lower temperatures solubility in some of the binary series may be considerably restricted. Thus Passerini,† who used much lower firing temperatures, found the solubility of MnO in MgO to be only about 26 mol.-%, and of MgO in MnO to be about 31 mol.-%. He also found only partial solubility between CaO and MnO.‡ Further, Frondel § found distinct evidence of exsolution of MnO from MgO in periclase from Langban, Sweden.

At the same time we have had indications of what may be an inherent instability of another type in solid solutions of the CaO–MnO series. Thus when pellets of these solid solutions are subjected to mechanical pressure, or to rubbing during grinding, a reddish-brown colour develops; for this reason considerable care was necessary in preparing powders for X-ray examination. Microscopic examination of the mixtures containing 20 and 40 wt.-% of CaO showed that the relatively coarse powder obtained by careful breaking-down was isotropic and of a pale green colour, whereas, in the case of the finely ground material obtained by vigorous rubbing, many of the grains had developed brown centres, some also having opaque particles dispersed in them. The edges of the grains tended to be birefringent and a few small individual yellow crystals of high birefringence were noted. No new phase could, however, be detected by X-rays in the rubbed material. To investigate the matter further, a solid solution containing 47·4 wt.-% of CaO was prepared. This gave 331 reflections almost touching the knife-edges with the manganese radiation used, and gave a lattice constant of 4·629 kX. units, this value being exactly that predicted from Vegard's law. After hard rubbing to give the brown coloration, no new phase or apparent spacing change on the X-ray film could be detected, but the high order lines now showed a progressive increase in diffuseness and the 331 reflections had almost disappeared. It should perhaps be pointed out that the degree of fineness produced by the rubbing was far removed from that at which normal line-broadening appears. In order to determine whether atmospheric oxidation was playing a part in the colour changes observed, a pellet of the green solid solution was rubbed by means of a steel rod in an atmosphere of hydrogen. It turned brown apparently as readily as when the rubbing was carried out in air.

To obtain further information, a pellet of MnO and one of the green solid solution containing 60 wt.-% of MnO were heated side by side on pieces of platinum foil in hydrogen for 2 hr. at 1200° C. The underside of the latter pellet was bleached where it had come into contact with the platinum, and in both cases there were indications that pick-up of manganese by the platinum had occurred. On heating the pieces of foil side by side in air, that which had been in contact with the solid solution developed a heavy black film of manganese oxide, while that which had been in contact with MnO alone developed only a thin, brown, translucent film, indicating that the solid solution gave up manganese more readily to the platinum than did the pure MnO. This is the reverse of what would normally be expected, as, in addition to the effect of dilution of MnO by CaO, the fact of formation of a stable solid solution with consequent decrease in free energy would be expected to decrease any tendency of MnO to break down.

The similar behaviour of CaO–MnO mixtures, containing 10–20 wt.-% of CaO, heated to the melting point on pieces of molybdenum, has already been described by one of the writers.‖ In these earlier experiments a clear indication of alloying of molybdenum and manganese was obtained, though with 100% of MnO no noticeable reaction was observed.

It would appear, therefore, that CaO–MnO solid solutions are of inherently low stability. In view

* J. R. Rait and H. J. Goldschmidt, *Journal of The Iron and Steel Institute*, 1945, No. I., p. 391 P.
† L. Passerini, *Gazzetta Chimica Italiana*, 1930, vol. 60, p. 535.
‡ L. Passerini, *ibid.*, 1929, vol. 59, p. 139.
§ C. Frondel, *American Mineralogist*, 1940, vol. 25, p. 534.
‖ J. White, *Journal of The Iron and Steel Institute*, 1943, No. II., p. 668 P.

of the behaviour of FeO in contact with CaO, one is naturally tempted to suggest a similar type of reaction between CaO and MnO, but there is as yet insufficient experimental evidence to establish this. Furthermore, the position is somewhat complicated by the fact that MnO alone on rubbing tends to develop a brown colour, at least in air.

AUTHORS' REPLY.

The AUTHORS wrote in reply: The authors thank Mr. Rooney, Dr. White, and Mr. Ford for their appreciative remarks on the data given in the paper. Dr. White and Mr. Ford discuss the closing of the two-phase field between CaO and MgO by the addition of MnO. The authors had this ternary system in mind when the binary systems were selected for examination and are pleased that the writers are also considering such work. They welcome the comments on the possibility of less than 100% solubility in these systems at lower temperatures. The work will require careful experimentation. Their observations on the effect of rubbing or grinding on CaO–MnO specimens in producing colour changes and marked diffuseness of the high-angle X-ray reflections are certainly intriguing. A brown surface film was found on some of our heat-treated samples and this was removed. The pieces used for the X-ray powder specimen did not show the effects described by Dr. White and Mr. Ford. It is possible that the differences observed on the ground powder are allied to the different initial calcination temperature—1200° C. as against 1350° C. in our experiments. The authors thank Dr. White and Mr. Ford for the detailed information given on the many points discussed.

Mineralogical Observations on Some Basic Open-Hearth Slags.

BY S. O. AGRELL, B.A., PH.D., F.G.S. (DEPARTMENT OF GEOLOGY, THE UNIVERSITY, MANCHESTER).

(*Journal of The Iron and Steel Institute*, 1945, No. II., pp. 19 P–55 P).

SYNOPSIS.

The principal phases that may occur in basic open-hearth tapping slags are lime, magnesio-wüstite, nagelschmidtite, di- or tri-calcium silicate, and apatite, with smaller amounts of monticellite, merwinite, and calcium ferrites. In the melting-down stage monticellite or, more rarely, merwinite and wüstite-magnetite solid solutions predominate in those slags in which no fluorspar has been used; in addition a phase is also recorded the properties of which most closely resemble those of steadite. The chemical composition, optical properties, and mutual relations of the above phases occurring in a number of slags are given, and the variations of phase assemblages from two casts are described in detail.

The variation of phase assemblages of these and other slags is summarized by plotting the different assemblages on the ternary diagram CaO–P_2O_5–SiO_2, and it is shown that they fall into definite fields on this diagram. With further study of the phase assemblages of slags the chemical compositions of which are known, this diagram could be amplified so that the phase assemblages of basic slags could be predicted from their chemical compositions.

Dr. J. WHITE (Sheffield University) wrote: Dr. Agrell's paper, besides giving a wealth of invaluable detail regarding relationships between the crystalline phases in specific slags, is an important contribution towards the elucidation of the general problem of the phase relations in the complete slag system, a statement of which, in terms of phase groupings or assemblages, has been attempted by the writer * and, in amended form, by Rait and Goldschmidt.† Such a statement is, of course, necessarily a simplified one in that the effects of solid solution, allotropic transformations, &c., are not fully indicated. Allowing for this limitation, the author's data are in the main substantially in agreement with the phase assemblages of Rait and Goldschmidt, except on one or two points of detail with respect to which it now seems likely that the phase assemblages will require to be amended. Our conception of the inter-relationships between the silicate and silico-phosphate phases has, for instance, been considerably modified as a result of recent papers. In particular, Bredig's work, to which the author refers, indicates that nagelschmidtite is a member of a solid-solution series continuous with a high-temperature, hexagonal form of dicalcium silicate. On cooling, this solid solution tends to break down into silico-carnotite and orthorhombic dicalcium silicate which is still capable of retaining appreciable phosphate in solid solution. At still lower temperatures the latter transforms in turn to the β-form.

On the whole, Dr. Agrell's observations tend to confirm these conclusions if they do not finally establish them, as he finds evidence of transformation in the nagelschmidtite of his slags and a significant replacement of nagelschmidtite by dicalcium silicate marginally. Some modification of the phase assemblages which indicate a composition range of coexistence of dicalcium silicate with nagelschmidtite of definite composition, will probably be necessary in this respect. Only short of complete equilibrium will dicalcium silicate and nagelschmidtite coexist. This can occur, owing either to a partial breakdown of nagelschmidtite in the solid state, or to an interruption in the crystallization of nagelschmidtite owing to the temperature dropping during freezing

* J. White, *Journal of The Iron and Steel Institute*, 1943, No. II., p. 579 P.
† J. R. Rait and H. J. Goldschmidt, *Journal of The Iron and Steel Institute*, 1945, No. I., p. 391 P.

from the range of stability of nagelschmidtite into that of dicalcium silicate. The observed juxtaposition of these two phases, which the author attributes to peritectic reaction in the system $2CaO.SiO_2$–$3CaO.P_2O_5$, can quite well be explained in terms of the latter sequence of events, namely, that the primary crystallization of nagelschmidtite was still proceeding when the temperature dropped below that at which nagelschmidtite is a stable phase. Crystallization of dicalcium silicate would then intervene giving the structures observed. This is equivalent to postulating a surface of primary crystallization from the liquid state of dicalcium silicate in the complete slag system, which is quite possible even though no direct crystallization of this phase from the liquid state can occur in the binary system $2CaO.SiO_2$–$3CaO.P_2O_5$. One other point may be commented on in this connection. As no association of silico-carnotite with the dicalcium silicate was observed in these slags it would appear that the solubility of phosphate in orthorhombic dicalcium silicate must be greater than is indicated in Bredig's qualitative diagram. The presence of fluorspar may, however, have accounted for this apparent anomaly.

In the presence of fluorspar, the relationships are, of course, appreciably different, in that fluorapatite is formed at the expense of the silico-phosphate, and the silicate occurs as a separate phase. The author's observations on this point are in general agreement with the writer's Fig. 22(*C*) (*loc. cit.*, p. 659 P), with Rait and Goldschmidt's Fig. 22, and with the phase assemblages, though the assemblages apply strictly to slags to which sufficient fluorspar has been added to decompose completely the silico-phosphate. One point remains to be settled, however, namely, that with small additions of fluorspar short of the amount required to give complete conversion of the phosphate to apatite and dicalcium silicate, one would not expect to find dicalcium silicate present but, rather, a nagelschmidtite solid solution of higher ratio of silica to phosphoric oxide than in the apatite-free slag. It is possible that the dicalcium silicate in such slags arises during a freezing sequence of the type described above.

Dr. Agrell's observations regarding the changes occurring in the nature of the silicates with decreasing CaO to SiO_2 ratio are in agreement with the phase assemblages in that dicalcium silicate is in turn replaced by merwinite and then by monticellite, both of which may have part of their MgO replaced by FeO and MnO. At the same time, the observations of several workers have suggested that, at a certain degree of lime deficiency, substitution for lime in the silico-phosphate also took place. Thus Schneiderhöhn, as mentioned by the author, found what he took to be substituted silico-phosphates in slags of low basicity, and Rait and Goldschmidt, though they found nagelschmidtite in slags containing merwinite, found that they got modified X-ray patterns for this silico-phosphate in synthetic mixes of it and merwinite. The author's observations confirm that such substitutions in nagelschmidtite can occur, and they also indicate that replacement of silicon by phosphorus can occur in such "mixed" silicates as monticellite as well as in dicalcium silicate. Furthermore, his identification of "steadite" in sample No. 2, cast 8609, suggests that at a certain CaO deficiency nagelschmidtite may cease to be stable, being replaced by a new phosphate or silico-phosphate. In this particular slag the deficiency of lime is such that, assuming satisfaction of the P_2O_5 with CaO to form $3CaO.P_2O_5$, the silicates present would be a mixture of monticellite and forsterite, both with a considerable replacement of MgO by FeO and MnO. The latter replacement is probably responsible for the fact that actually only one silicate was observed, as such replacement will tend to remove the insolubility between forsterite and monticellite as indicated in Fig. 7(*A*) of the writer's paper (*loc. cit.*, p. 596 P).

Dr. Agrell found that $3CaO.SiO_2$ was generally absent from his slags, dicalcium silicate occurring along with free CaO. This agrees with Rait and Goldschmidt's observations on open-hearth slags, though they found that $3CaO.SiO_2$ occurred in their oxidizing electric slags. They attributed its absence from the open-hearth slags to the absence of a surface of crystallization from the liquid state of $3CaO.SiO_2$ in the thermal equilibrium diagram of these slags (pointing out that such a surface did not exist in the ternary system CaO–P_2O_5–SiO_2), and to the sluggishness of its formation in the solid slag. They therefore included it in their phase assemblages as the present writer had done. While this explanation is, of course, a possible one, it would appear that the absence of $3CaO.SiO_2$ from certain slags may be due to a more fundamental reason. Thus the slags in which it has been reported have generally been low in phosphorus (*e.g.*, Rait and Goldschmidt's electric slags and Mason's open-hearth slags), while those from which it has been absent have been relatively high in phosphorus (the open-hearth slags of the author and of Rait and Goldschmidt). It may therefore be that $3CaO.SiO_2$ is actually unstable in slags containing much phosphorus. Thus, although the reaction

$$CaO + 2CaO.SiO_2 = 3CaO.SiO_2$$

can proceed in the pure system CaO–SiO_2 at suitable temperatures, there is reason to believe that the free energy change associated with it is small (*see* the present writer's paper, *loc. cit.*, pp. 649 P–650 P). It seems quite likely, therefore, that when tricalcium phosphate forms a solid solution in dicalcium silicate, the resulting drop in free

energy may be more than sufficient to nullify the small free energy change associated with the formation of $3CaO.SiO_2$. If this is so, some modification will be required of the writer's Figs. 14(*B*) and 22(*C*) and Rait and Goldschmidt's Fig. 22, in that the tie from $3CaO.SiO_2$ to nagelschmidtite of composition $9CaO.P_2O_5.3SiO_2$ will have to be replaced by a tie to some point on the silico-phosphate join nearer to the composition of dicalcium silicate, this point corresponding to the P_2O_5 content at which $3CaO.SiO_2$ ceases to form from the orthosilicate and CaO. When sufficient fluorspar is present, causing breakdown of the silico-phosphate solid solutions with formation of dicalcium silicate, $3CaO.SiO_2$ may become stable and, in fact, it has been reported in apatite-bearing slags.

Like earlier workers who have used petrological methods, Dr. Agrell has failed to find spinel in any of his slags, although calculation on the basis of the phase assemblages shows that spinel should have occurred in some of his low-lime slags. Rait and Goldschmidt claim definitely to have identified spinel in some of their slags, and this is shown in the appropriate composition-range of their phase assemblages. Besides this, we now have sufficient knowledge of the simpler component systems to predict with some degree of certainty that spinel should occur in this particular range of composition. One point must, however, be borne in mind with regard to such predictions and calculations from the phase assemblages, namely, that in making them no allowance is made for possible solubility of the R_2O_3 oxides in the magnesio-wüstite phase; such solubility may be appreciable, especially when the latter is high in MgO or FeO. The magnesio-wüstite analyses of the author's Table IX., like those of earlier workers, do actually show appreciable Fe_2O_3 and Al_2O_3 contents, though whether these are wholly in solution in the magnesio-wüstite or as constituents of a separate phase intimately intermixed with the magnesio-wüstite would perhaps be difficult to decide with certainty.

The evidence produced by the author that solid lime, as distinct from undissolved xenoliths, was actually present in some of his slags at working temperature is a direct confirmation of Jay's finding on this point,* as is his observation that this lime tends to deposit magnesio-wüstite from solution during cooling. The finding that solid phases may be present in the liquid slag in the furnace is an important one and must materially influence our approach to slag–metal equilibrium relationships in the basic open-hearth furnace, since the presence of solid lime or silico-phosphate automatically fixes the activity of these constituents in the liquid slag, and this means that we must apply the concepts of heterogeneous equilibrium to the slag, as distinct from those of homogeneous equilibrium as has been customary hitherto.

Mr. M. A. Bredig (Vanadium Corporation of America, New York) wrote: The author has presented a careful discussion of his observations in the light of various recently proposed equilibrium diagrams of the system $CaO–SiO_2–P_2O_5$. The writer believes, as does the author, that these observations are not in good agreement with the relations between nagelschmidtite and dicalcium silicate described by Barrett and McCaughey, or by Trömel. He is happy to add the remark that the one discrepancy that Dr. Agrell found to exist with the writer's suggestions, namely, the observed occurrence of a peritectic relationship between nagelschmidtite and α-(ortho.)$2CaO.SiO_2$ may be considered to have been resolved in the meantime by considerations which were published by the writer last year.†

In an interpretation of X-ray and other data, the writer has then concluded that a peritectic relationship can exist between α-Ca_2SiO_4 (the phase identical with α-(hex.)$2CaO.SiO_2$, and with nagelschmidtite) and α'-Ca_2SiO_4 (or α-(ortho.)$2CaO.SiO_2$), by showing that merwinite is most likely an α'-Ca_2SiO_4 phase containing Mg_2SiO_4 in solid solution.* It seems very likely that in most of the slags examined by Dr. Agrell the presence of Mg, Fe, Mn, &c., has, even in the simultaneous presence of P_2O_5, sufficiently altered the relationship between these two phases from that assumed by the writer to exist in ternary compositions $CaO–SiO_2–P_2O_5$ to the peritectic relationship assumed in the $CaO–MgO–SiO_2$ system. An experimental investigation of the quaternary system $CaO–MgO(FeO,MnO)–SiO_2–P_2O_5$ would help to ascertain the correctness of these assumptions. Until such information is available, the observations reported by the author may be considered as a confirmation of the occurrence of various inversions and peritectic reactions at temperatures below the liquidus, very much like those proposed by the writer.

AUTHOR'S REPLY.

Dr. Agrell wrote in reply: I have read the remarks of Dr. Bredig and Dr. White with much interest and am glad to find them in general agreement with the observations put forward in the paper. Their suggestions will be borne in mind in my future work on slag mineralogy. I

* A. H. Jay, *Journal of The Iron and Steel Institute*, 1945, No. I., p. 505 P.

† M. A. Bredig, *Journal of Physical Chemistry*, 1945, vol. 49, p. 541, Fig. 1; *Transactions of the American Institute of Mining and Metallurgical Engineers*, 1944, vol. 158, p. 95.

should welcome samples of analysed slags, preferably uncrushed, to enable me to extend my mineralogical observations which so far have covered only a limited number of slags.

The Hot-Strength Characteristics of Moulding Sands.

By W. DAVIES, Ph.D., M.Sc., F.G.S., and W. J. REES, D.Sc.Tech., F.R.I.C. (University of Sheffield).

Paper No. 15/1945 *of the Steel Castings Research Committee (submitted by the Moulding Materials Sub-Committee).*

(*Journal of The Iron and Steel Institute*, 1945, No. II., pp. 61 P–70 P.)

Synopsis.

This paper summarizes the results so far obtained in the research on the hot-strength characteristics of moulding sands which is in progress at Sheffield University. A description of the apparatus employed is given. Attention has so far been directed towards the differences between the hot-strength characteristics of the various clay bonds in relation to their mineralogical constitution. All the bonds so examined show a gradual increase in strength with rise of temperature. After a maximum strength is reached, the strength decreases rapidly. This peak hot strength is attained at a temperature of 900–1000° *C. for clays having the silica–gibbsite–silica structure,* e.g., *montmorillonite or secondary mica, and at a temperature of more than* 1150° *C. for clays having the silica–gibbsite,* i.e., *kaolinite, structure.*

Mr. D. C. Williams (East Mechanical Laboratory, Cornell University, Ithaca, New York) wrote: The writer has done some testing of foundry sands for hot compressive strength data, and therefore found the paper of Dr. Davies and Dr. Rees very interesting.

The authors use the B.C.I.R.A. test-piece which from the dimensions given in the text and from Fig. 1 must be 1·128 in. in dia. and 2·256 in. tall. Those dimensions are reasonably close to the dimensions (1·125 in. in dia. and 2·0 in. tall) of the hot compressive strength test-piece commonly used in the United States, the two types of test-pieces thus having comparable dimensions.

It is a little puzzling as to how the standard A.F.A. rammer (2 in. in dia.) could be used to ram a test-piece 1·128 in. in dia. The falling weight of the standard A.F.A. rammer is 14 lb., whereas the falling weight of the rammer (not standard) used to compact the 1·125 × 2 in. test-piece is 7 lb. Since the authors state that a standard A.F.A. rammer was used, more ramming energy was given the B.C.I.R.A. test-piece per ram than that given per ram to the test-piece used in the United States. This variation points out a dissimilarity between the two types of test-pieces.

As for the technique of ramming, it is not clear to the writer how the test-piece was rammed. The authors state "five blows were given to each end of the core box, the blows being alternately on one end and the other." This of course is not a standard A.F.A. procedure and may be an improvement upon our ramming method. The blows being given to the ends of the core box suggest a jolting procedure rather than ramming conducted directly upon the sand.

According to A.F.A. procedure * a dried test-piece is one that has been dried at 105–110° C. The authors dried their test-piece at 200° C. (in United States practice this temperature is well into the "baking" range). Preheating to such a temperature above that required to eliminate the mechanically held moisture might have some effect upon the materials that would not occur when heated only to 110° C. Grim and Rowland † indicate that there is some kind of reaction taking place for the commonly used clay minerals between 100° and 200° C.

The B.C.I.R.A. and A.F.A. test-pieces have comparable dimensions but the type of rammer used to fabricate the test-pieces, the method of ramming them, and the drying temperature for the test-pieces, vary to a great degree.

The use that has been made by the authors of contour graphs for the plotting of hot compressive strength data is excellent. The complete data can be accurately analysed at a glance. We in the United States would do well by considering this method of data presentation.

The writer has constructed Table A in which his results are compared with those of Dr. Davies and Dr. Rees. This table was constructed knowing that dissimilarities occurred in the two techniques of fabricating the test-pieces. Also, dissimilarities are present in the mixtures used, but they are probably not as important as those variations first mentioned. The hot compressive strength results are reported in pounds per square inch and on the basis of the original cross-sectional area (nominal area) of the test-piece. The writer's present experiments indicate that this should be remembered.

From Table A it will be seen that both sets of data agree well as regards (1) actual test values, or (2) general trends. One assumption has been made, namely, that Fulbond No. 1 and southern bentonite are relatively similar materials.

There are at least two questions which confront those interested in an elevated-temperature test upon foundry sands:

(1) What information does the foundryman desire to obtain from a hot compressive strength test, or some other test?

* "Foundry Sand Testing Handbook," p. 109. Chicago, 1944: American Foundrymen's Association.

† R. E. Grim and R. A. Rowland: *American Mineralogist*, 1942, vol. 27, No. 11, pp. 746–761.

(2) Can a suitable simple laboratory test be devised which will give an answer to the majority of the problems?

Among the writer's acquaintances in the foundry industry there appears to be as many different ideas as acquaintances, pertaining to what information an elevated-temperature test should provide. Opinions (not facts) are divided as to whether under a given set of conditions one needs to increase or decrease the hot-strength of a sand mixture. At the present time a simple observation test conducted, using any suitable furnace, provides a large amount of useful information concerning the behaviour of at least the surface of the test-piece.

A great amount of work must be done before an answer to question (2) is evolved. It is not outside the realm of possibility that the strength of the test-piece will eventually be obtained at room temperature following a previous exposure to elevated temperature.

The writer, as well as many others, has found that the addition of silica flour to a mixture increases the hot-strength. If the amount of clay bond in the mixture has not been altered, when comparing mixtures with or without silica flour, the same amount of glass-forming material is present. Since silica-flour additions to mixtures (glass-forming material being constant) increases the hot-strength, this increase must be due to a change in structure of the sand.

If erosion of the mould by liquid metal is a problem, one logical approach is from a structural viewpoint. Erosion takes place during such a short interval of time, that conducting a "hot-strength" test for that time interval would be testing a test-piece at relatively low temperatures far below that of liquid metal. It would thus appear that the addition of a suitable amount of larger grains would improve the knitting together of the sand. Large grains provide larger voids in the mixture; this is an advantage for feeding the solidifying mass, since the rate of heat dissipation is decreased, slowing down the freezing-off of the opening to the casting.

Dr. Davies and Dr. Rees indicate that their paper contains just the beginning of their investigations. The writer looks forward to their succeeding reports concerning this problem.

TABLE A.—*Comparison of Hot Compressive Strength Results of Messrs. Davies and Rees with those of the Writer.*

Time of Heating Test-Piece, min.	Temperature Control Setting, ° F.	Hot Compressive Strength, lb./sq.in.			
		Davies and Rees (10 Blows).	The Writer (6 Blows).	Davies and Rees (10 Blows).	The Writer (6 Blows).
		5% Western Bentonite, 95% Chelford Sand, 5% Moisture.	4% Western Bentonite, 95% N.J. No. 60 Sand, 5% Moisture.	5% Fulbond No. 1, 95% Chelford Sand, 5% Moisture.	4% Southern Bentonite, 95% N.J. No. 60 Sand, 5% Moisture.
2	1600	150	97	100	27
8	1600	350	322	225	142
16	1600	525	525	>350	207
2	2000	<50	122	<100	47
8	2000	175	217	<100	27
16	2000	200	208	<100	72

AUTHOR'S REPLY.

Dr. DAVIES wrote in reply: The B.C.I.R.A. core-box employed in the investigation consists of a brass tube 1·128 in. internal dia., the ends being closed by steel plugs which are a sliding fit in the tube and project beyond its ends. This core-box, containing the requisite quantity of sand, will just slip between the base-plate and plunger of the standard A.F.A. rammer; the ramming blow is transmitted to the sand through the plugs. After each blow, the core-box is turned end for end, this procedure being adopted as a result of work on the packing of sands during ramming (*see* W. Davies and W. J. Rees *).

The drying (or baking) temperature employed is usual in sand testing in this country, and is, I believe, adopted as being roughly comparable with foundry drying stove conditions.

I regard Table A as an extremely valuable contribution. In view of the differences in technique, the similarity between the results of western bentonite is striking. The difference between the data for Fulbond No. 1 and southern bentonite may be due to the presence of calcite in the former.

The ultimate aim of moulding materials research should be to treat the construction of a mould or core as a problem in the strength of materials. Perhaps someday it will be possible for the foundryman to look at a new mould design and decide without experiment just what properties are

* *Journal of The Iron and Steel Institute*, 1944, No. II., p. 19 P.

required in the moulding material for that particular job. If the moulding material is selected properly, there should be no erosion by molten metal, the casting should be sufficiently well supported to resist distortion, and yet the mould should accommodate the shrinkage during cooling without the development of hot tears. Strength of materials formulæ are usually semi-empirical in character; at present the empirical basis is lacking and must await the correlation of foundry trials with elevated-temperature laboratory tests.

The Tinning of Cast Iron.

By R. A. CRESSWELL, M.Sc. (Tin Research Institute, Greenford).

(*Journal of The Iron and Steel Institute*, 1945, No. II., pp. 157 P–169 P.)

Synopsis.

The quality of hot-dipped tin coatings on cast iron after different pretreatments is investigated, using the criteria of continuity of coating, rust resistance, and adhesion. The nature of the bond between tin and cast iron is also studied, by microscopical examination.

The poor tinning quality of cast iron is shown to be caused mainly by the presence of graphite flakes and to be intensified by contamination of the iron surface by graphitic sludge after pickling in acids. Investigation of modifications of the ordinary tinning processes shows that improved tin coatings can be obtained by reducing the duration of pickling in acids to a minimum; this is facilitated by good mechanical cleaning. The best pickling agent is found to be a cold mixture containing 5 *vol.-% sulphuric acid and* 5 *vol.-% hydrofluoric acid. The corrosion-resistance and adhesion of coatings obtained by such modifications of ordinary methods are, however, still low.*

Two new methods of preparing cast iron for tinning are described, both involving treatment in molten salts. The chloride method consists of immersing the article in the fused zinc-chloride/sodium-chloride eutectic mixture at 300–350° *C., followed by dipping in tin, covered with a layer of the same fused salt mixture, at* 300° *C. This method gives adherent protective coatings of tin on cast iron which has been well cleaned mechanically. When the cast iron is bonded to white metal, consistent adhesion values of from* 2 *to* 2·8 *tons/sq.in. are obtained. The chloride method can be adapted to tinning by wiping.*

The nitrate method was developed to give highly adherent coatings of tin and involves the following steps: Light pickling in acid to "open up" graphite flakes; immersion for 15 *min. at* 300–350° *C. in fused sodium-nitrate/potassium-nitrate eutectic mixture in order to oxidize surface graphite; pickling in dilute hydrofluoric acid to remove the scale formed in the nitrate bath; fluxing and tinning. Adhesion values of up to* 3·8 *tons/sq.in. are obtained between tin-base bearing alloy and cast iron tinned by this method. Microscopical examination of the bond shows that the tin penetrates cavities formerly occupied by graphite.*

Dr. C. E. Homer (Messrs. Darwins, Ltd., Sheffield) wrote: The processes described appear to constitute a major advance on those previously available, and should extend the application of hot-tinning in this field. There is one practical point in connection with the chloride process which has not been mentioned by the author, although one would have expected it to be of some importance, namely, the contamination of the tinning bath by gritty tin–iron compound in large-scale operation. With the conventional process, traces of iron chloride are introduced into the bath on the surface of the pickled, washed, and fluxed article, and it is generally assumed that it is the reaction between the iron chloride and the molten tin which produces the tin–iron compound. The accumulation of the compound affects the finish of the work, and in order to remove it the bath has to be treated periodically.

One would expect rather more iron chloride to be carried over into the tin bath in the fused-chloride process, particularly when the salt bath has had considerable use. It would be interesting therefore to know whether the author can give any information as to how the fused-chloride process compares with the conventional one and what precautions he advises to minimize compound formation. It is also important to know how to decide when the salt has become unfit for further use.

Mr. P. Attenborough (International Meehanite Metal Co., Ltd., London) wrote: Any contribution such as Mr. Cresswell's, which considers rationally an industrial technique of an empirical character is of undoubted value.

In referring to adhesion values of white-metal-lined bearings stated in the paper, certain comments upon testing seem pertinent. In Table II., where six adhesion values are given per specimen, the range of results within each group varies from 7½ to 59%, ignoring test data where either eccentricity of test-piece or entrapped oxide is quoted.

Is it considered that this lack of uniformity is a measure of a corresponding variation in the bonded surface of the specimen? If so, equal consideration must be given to the range values of test results as to the average adhesion strength in assessing the merit of any tinning process.

Alternatively, the variation in adhesion values may be inherent to the testing method, which requires small specimens. For instance, the cross-sectional area of a test-annulus machined to ½ in. external dia., and $\frac{5}{16}$ in. internal dia. is only 0·12 sq. in., and the accuracy of machining required would appear to involve practical limitations as a routine test-method.

A third possible cause of variation may be derived from stress imposed by machining; *e.g.*, a number of results in Table II. are invalidated owing to the lining being forced off in sawing and drilling. It is suggested that machining stresses may not always be manifest so obviously, but may nevertheless be of sufficient magnitude to influence test values.

Lastly, permission is sought to include a number

of test results obtained by the research organization with which Mr. Cresswell is associated and by the same method already discussed. These were done primarily to determine the effect of graphite size of the cast-iron sample upon adhesion values.

The two factors affecting graphite flake considered were (*a*) the effect of casting mass, and (*b*) the influence of metal process, employing both normal and high-duty cast iron. Comparison was also made with white-metal-lined specimens that had been previously electroplated with successive layers of iron and copper, each layer being approximately 0·001 in. thick, and deposited under well-controlled conditions.

The compositions of the test materials selected were as follows:

	Total Carbon, %.	Silicon, %.	Manganese, %.	Phosphorus, %.	Tensile Strength, tons/sq.in. (0·875-in. dia. B.S.I. test-bar).
Grey iron No. 1	3·68	2·00	0·60	0·39	13·4
Grey iron No. 2	3·25	2·92	0·55	1·03	12·6
*High-duty iron *E*	3·33	2·20	0·75	0·21	16·2
*High-duty iron *C*	3·10	1·92	0·76	0·16	19·8
*High-duty iron *A*	2·98	1·45	0·90	0·12	24·8

* The high-duty irons were made by the Meehanite process.

The test results are presented in Table B, and give rise to the following comments:

(1) Adhesion values of the nitrate method are approximately $1\frac{1}{2}$ times as large as those of the chloride method.

(2) Specimens plated with consecutive layers of iron and copper, under optimum conditions, and hot-tinned, gave adhesion values only one-half those of samples tinned by the nitrate method and are lower than the values given for high-tensile irons tinned by the chloride method.

(3) Results from the nitrate method are fairly constant irrespective of casting section and metal process. The "keying effect" of tin penetrating cavities previously occupied by graphite does not increase as the graphite content of the iron increases, *i.e.*, for the lower tensile irons, Nos. 1, 2, and *E*, or as the original casting mass increases.

It has been suggested that some of the flux and fused salts remain in large graphite cavities and prevent the maximum potential bond from being obtained.

Although metal type does not apparently affect the bond-adhesion value, selection of the backing metal for cast-iron bearing shells should be made so as to obtain maximum strength and solidity.

(4) Values given by the chloride method are highest where conditions favour the formation of small graphite flakes. Bond strength is a maximum for all types of cast iron in thin-section specimens and, for high-duty irons, in specimens of both thin and heavy sections.

AUTHOR'S REPLY.

Mr. Cresswell wrote in reply: Dr. Homer raises an interesting point in the possibility of contamination of the tin by pick-up of iron in the fused chloride bath. Some contamination does occur, but if the salts are contained in a Monel-metal pot, the contamination is no greater than that encountered with normal tinning procedures. Analysis of the salts after $2\frac{1}{2}$ months' continuous use in a Monel-metal container gave 0·1% of

Table B.—*Results of Adhesion Tests on Specimens Tinned by Various Methods.*

Material.	Tinned by Chloride Method.					Tinned by Nitrate Method.					Iron and Copper Plated, and Tinned.				
	Test Adhesion Values, tons/sq.in.				Average Adhesion, tons/sq.in.	Test Adhesion Values, tons/sq.in.				Average Adhesion, tons/sq.in.	Test Adhesion Values, tons/sq.in.				Average Adhesion, tons/sq.in.
Thin specimens, $2 \times 3 \times \frac{5}{8}$ in. as-cast, machined to $2 \times 3 \times \frac{1}{4}$ in.															
No. 1.	2·1	1·3	1·3	1·2	1·5	2·4	2·9	3·4	1·8	2·6	...	...	...	...	...
No. 2.	2·2	1·8	1·6	1·2	1·7	2·5	3·0	3·4	2·4	2·8	...	...	...	...	...
E.	1·8	2·0	2·0	2·0	2·0	2·2	2·8	3·2	3·2	2·9	...	...	...	...	...
C.	1·9	1·6	2·2	2·1	2·0	3·0	3·0	3·3	3·4	3·2	...	...	...	...	...
Heavy specimens, $2 \times 4 \times 2$-in. blocks as-cast, machined to $2 \times 3 \times \frac{1}{4}$ in. Test-pieces taken from interior of block.															
No. 1.	1·1	1·2	1·9	1·1	1·3	2·2	...	...	2·1	2·2	1·2	1·2	1·2	1·0	1·2
No. 2.	1·2	1·2	1·2	1·1	1·2	3·3	3·6	3·2	3·7	3·5	1·0	1·1	0·9	0·8	0·95
E.	1·2	1·2	2·0	0·9	1·3	2·8	1·8	2·4	2·6	2·4	1·7	1·2	1·2	1·1	1·3
C.	1·5	2·4	1·7	2·2	2·0	2·2	3·6	2·9	2·5	2·8	2·1	1·1	1·0	1·1	1·3
A.	2·8	1·2	1·2	1·9	1·8	3·0	2·3	2·6	2·3	2·6	1·0	1·1	1·1	1·9	1·3

iron, less than 0·1% of copper, and a trace of nickel; this concentration of impurity was not harmful in any way. Apart from occasional additions to compensate for "carry over," the salts were not renewed for over 18 months and the bath was still in good working condition.

On the other hand, in an iron or steel container the salts rapidly became contaminated with iron, and gave rise to a gritty tin bath; after 20 hours' operation the salts had picked up 0·89% of iron; in this condition the bath still cleaned the cast iron satisfactorily, but led to very rapid contamination of the tin.

I am grateful to Mr. Attenborough for adding some further results of adhesion tests which were obtained in collaboration with him after the paper had been submitted for publication. I am in agreement with his comments on these results. With regard to the method of adhesion testing, the variability of results due to factors inherent in the testing method is difficult to assess when testing on cast iron, owing to the rather large variation of metallurgical bond. Using a more uniform backing material, namely, mild steel, the variability of adhesion test results has been investigated by Forrester and Greenfield and will be discussed in a paper to be published shortly. Mild-steel plates were lined under various conditions with the 7% antimony, 3½% copper alloy used in my experiments. Sixteen tests were made for each set of conditions and from these results an estimate was made of the standard deviation; with the best lining technique this value was found to be 4·5%. Thus the probability is that 95% of the determinations should fall within ±9% of the mean. The variation shown in my figures is clearly greater than this, suggesting that the main proportion of the variation is due to actual differences in bond strength from place to place.

The Design and Performance of Some Commercial Optical Pyrometers of the Disappearing-Filament Type.

By C. R. BARBER, B.Sc. (National Physical Laboratory).

Paper No. 18/1946 *of the Steel Castings Research Committee* (*submitted by the Foundry Steel Temperature Sub-Committee*).

(*Journal of The Iron and Steel Institute*, 1945, No. II., pp. 171 P–188 P.)

Synopsis.

A critical examination has been made of five models of commercial portable optical pyrometers of the disappearing-filament type, with reference to the design of the lamp, the optical system, the monochromatic and neutral filters, and the measuring system.

It has been shown that in many cases the lamp filaments are too short to be free from end-effect, and the advantages of the use of a flat-filament in this and other respects are discussed. The size and position of the diaphragms of the optical system were in some examples not in accordance with those necessary for obtaining perfect disappearance of the filament. The transmission curves of the monochromatic and neutral filters are given, and the requirements of the combination of the two filters are examined. A current or voltage calibration of the lamp may be employed and the advantage of the latter for short filaments is pointed out. The potentiometer method used in one pyrometer has considerable merit.

Dr. E. J. Sandford (Hard Metal Tools, Ltd., Coventry) wrote: This paper is of great importance in demonstrating that optical pyrometers of commercial manufacture are by no means as carefully designed or as accurate as users often believe. On reading Mr. Barber's list of defects, which covers the lamps, filters, absorption screens, optical systems, &c., it is apparent that these instruments are not designed in accordance with well-known scientific principles, but are made more or less empirically. It is unfortunate that the author was not able (for obvious reasons) to add to the usefulness of his paper by stating the maker's name for each pyrometer, but it is to be noted that pyrometer E was much superior to the others, and it would be interesting to know whether it was of British or foreign manufacture.

The use of high temperatures, both commercially and in research, is becoming more commonplace, and the demand for the accurate measurement of temperatures between 2000° and 3000° C. is growing. In my experience, it is practically impossible to measure such temperatures with a greater accuracy than ±50° C. with commercial instruments, mainly because there is no method of calibration on which greater reliance can be placed. The usual procedure adopted by manufacturers of optical pyrometers seems to be to extrapolate from the highest temperatures of the standard tungsten lamp (about 2000° C.). In view of Mr. Barber's disclosure of the variation of the absorption factor of some instruments, it can readily be seen that extrapolation from 2000° to 3000° C. is subject to great errors. Even at lower temperatures my Company has had difficulty in obtaining a reliable calibration. Pyrometers newly calibrated by the manufacturers have been checked against a standard tungsten lamp (calibrated by the National Physical Laboratory), and differences of 60–70° C. at 1500° C. have been found. In fact, it is apparent that too little regard is paid in this country to the accurate measurement of high temperatures.

Referring to the effect of the filament length on the time to reach equilibrium temperature, I should like to know whether it is a satisfactory procedure to run the filament to, say, 100° C.

above the temperature to be measured and to approach the disappearance point from the higher temperature. It would appear that the time lag can be reduced by this method.

In Fig. 4 of his paper Mr. Barber has shown the exit and entrance angles as the angle subtended by the diaphragm at the filament or nearest lens. I should like to know whether the diameter of the objective and eye-piece was large enough, in all cases, to cover the entrance and exit cones respectively. In one pyrometer examined in my Company's laboratories, the diaphragm was so large that the entrance cone when projected in the plane of the objective lens was greater than the diameter of this lens. This discrepancy was more pronounced than that shown in Fig. 4(*b*) of the paper.

Mr. W. M. Barratt (Hard Metal Tools Co., Ltd., Coventry) wrote: Mr. Barber's paper has been read with considerable interest by us for we have in use in our works several disappearing-filament optical pyrometers and his investigations coincide with some that we have carried out. Our tests, however, have been more in the nature of workshop practice and consequently have not the same degree of accuracy as his. He may find our comments of interest and will be able to compare them with his own and with others.

We have in regular use, at present, instruments of this type made by a very well-known English manufacturer and also some made by a well-known German firm. In other works, in the past, two other English types have been used, one of which was not very popular for our type of work; the other was useless. It was found impossible to focus the eye-piece of the last-named so as to get the filament to disappear and it was tiring to the eyes.

The German instrument is the most popular because of its ease in matching, complete disappearance of the filament when matched, consistency in readings, wide scale, anti-parallax mirror on the scale, current scale, and low thermal lag. The thermal lag, incidently, is opposite to the others, *i.e.*, the reading falls about 10° C. in about 2 min. The disadvantages (though not serious ones) are: The indicator is separate to the sighting tube, the moving-coil system has a "set-up" zero, and the image in the sighting tube is inverted.

It is hoped that this long-delayed investigation will be seriously considered by the manufacturers, because we feel that if sufficient interest could be aroused among them, the user, and the N.P.L., an instrument of English manufacture could be marketed that would compare favourably with the foreign one mentioned by Mr. Barber.

If our presumption of the make he mentions is correct, the improvements incorporated in the present instrument appear to be due to co-operation between the maker and the Bureau of Standards after their investigations by Fairchild and Hoover.

It is a particularly good instrument for presision work, but its price in Britain is about three times the cost of the English make and so it may not be worth the extra expense where repetition and ordinary industrial accuracy are concerned.

We, as users, are not satisfied with the instruments in use. The complete disappearance of the filament is often very difficult and sometimes impossible; thermal lag is serious, and mechanical balance is sometimes troublesome. As can be expected, each instrument has its own characteristics which can be discovered only by careful investigation and by recording the results. One notable instance of this is the thermal lag which can be from 10° to 25° C. in temperature indications, and varying in time (for a steady reading) from ½ to 3 min., depending on the temperature between 1100° C. and 1600° C., and on the particular instrument. We have also found that instruments that have been in use, on and off, for 4 or 5 years "creep" more than those that have been purchased later. The newer instruments, however, are more difficult to match owing to the bright "reflection" lines around the edges of the filaments. This, of course, means that no two observers get the same reading.

In addition to the difficulties mentioned, more attention should be given to the monochromatic glasses. We have double-ranged instruments and the same monochromatic glass is used for all temperatures with the result that, when the higher temperatures are being checked, colour effect becomes evident and disappearance of the filament is impossible. In the German instrument there are two red glasses, one thicker than the other, which are changeable merely by rotating a ring on the sighting tube. This helps considerably in ease of matching.

Another difficulty has been experienced: When the eye is (presumably) placed centrally in the eye-piece and the filament focused and matching the image, any slight movement of the head puts the filament out of focus and upsets the matching. This appears to be due to the lenses and to reflection, because, when the filament is sighted on the image (and with no current passing through) with the head in one position and the filament appearing as a well-defined, black object superimposed on the luminous background, a slight movement of the head will show part of the filament slightly luminescent and the other part black. This is when considering the thickness of the filament at the point where matching is usually made. With the German instrument, a diaphragm is fitted between the eye and the monochromatic glass so that the eye is automatically centralized.

Lastly, we are concerned with the checking of the instruments above the safe temperature (maximum) of 2100° C. for the tungsten-strip lamp. There appears to be no satisfactory method between the temperature of 2100° C. and that of the carbon arc, except, perhaps, iridium (which has been given as $\pm 3°$ C. at 2454° C.) and tungsten melting points. There seems to be no great certainty about the temperature of the carbon arc. Investigators in the U.S.A. give different results, their temperatures varying from 3811° K. (International Temperature Scale) to 3829° K. Kahy and Laby give a figure of 3400° C., and 3600° C. when under pressure. It appears that much care has to be taken over the purity and thickness of carbon, the maximum current flowing, arc voltage, and relative positions of the positive and negative tips.

We are interested in temperatures of 2500°–3000° C. and no doubt many others are, or will be, concerned with these higher limits; it will be interesting to hear Mr. Barber's opinion and whether any investigations in this range are being made. We feel that extrapolation is theoretically sound, but with the filters, and combinations of them, errors can creep in owing to transmission curves differing, to absorption and/or reflection effects, or to any other unknown effects which make commercial practice differ from a theoretical thesis. An investigator in America has obtained good results from his experiments on a carbon tube furnace operating at 3000° C. and, using a radiaton pyrometer, he found a close relation between kilowatt power input and temperature.

Some of the effects we have mentioned may not be experienced by other users because the objects they are sighting differ so much from ours, and it has been proved that with different-sized objects the effects differ. We sight onto a luminous segment which is under "black-body" conditions and about $\frac{3}{4}$ in. wide, but the temperature variation from the outer and inner edges to the centre varies over about 100° C. so that filament thickness is important to us. We get different results at times when sighting on our strip-filament test-lamp and on a furnace. Most of the troubles appear to be due to the entrance and exit angles and to the lamp filaments, as mentioned by Mr. Barber, but improved coloured glasses and filters would help considerably.

We know that the manufacturer of our English make is investigating the possibility of fitting flat-sided lamps, but, as in the case of lenses and filters, they are dependent on the lamp and glass manufacturers who have their own difficulties. It is hoped, though, that the interest shown in Mr. Barber's paper, and the various experiences mentioned by users, will produce effective results.

AUTHOR'S REPLY.

Mr. Barber wrote in reply: It is interesting to have on record the experiences of users of commercial disappearing-filament optical pyrometers and to note the confirmation of many of the defects of the instruments set out in the paper.

With regard to thermal lag of the lamp filament, I think the course suggested by Mr. Sandford of approaching the matching point from about 100° C. above the temperature would reduce the lag error somewhat, although no expedient of this nature can completely overcome this inherent defect. The observations concerning the excessively large apertures in some pyrometers serve to emphasize the apparent absence of the use of any guiding principles in deciding on the size of diaphragms to be employed.

The problem of very high temperature measurement (2000° C. upwards) with many of the existing optical pyrometers is somewhat difficult, mainly on account of the poor quality of the absorption glasses and the absence of a suitable calibrated source. Mr. Sandford's statement that there is no great certainty about the temperature of the carbon arc is hardly borne out by the figures which he quotes. The divergence of $\pm 10°$ on a mean value of 3820° K. for four independent determinations of the point is equivalent to a divergence of $\pm 1\frac{1}{4}°$ C. at the melting point of gold, the fundamental point of the scale, on which all temperatures above the gold point are based. When the errors of extrapolation are taken into account it is evident that the spread of 20° at the arc point is not serious. It seems clear that when the necessary precaution of employing high-purity carbons is observed and the operating conditions are such as to produce a steady arc without hissing, the arc point provides an excellent check for the extreme high-temperature range. We have recently made a determination of the temperature of an arc at the National Physical Laboratory and a value within the limit of $\pm 10°$ on 3820° K. was obtained. Acheson graphite electrodes were used, the positive being $\frac{1}{4}$ in. in dia. and the negative $\frac{1}{8}$ in. The latter burnt away rather rapidly and continuous hand control was necessary to produce a steady arc, but with a little practice in determining the correct relative positions of the electrodes, a uniformly bright disc filling the entire crater may be maintained. If the absorption constant for the pyrometer is determined at the arc point and up to the limit of the tungsten-strip lamp's range, interpolation in the region 2000–3000° C. should be possible without serious error.

Further Correspondence on

A Rapid Method of Ore Testing. The "S.K." Porosity Test.

By H. L. SAUNDERS, Ph.D., F.R.I.C., and H. J. TRESS, Ph.D. (Imperial College, South Kensington).

(*Journal of The Iron and Steel Institute*, 1945, No. II., pp. 291 P–300 P).

Synopsis.

An apparatus is described for the rapid determination of the porosity of ores by what is known as the "S.K." (South Kensington) test. The principle of the test is to fill the voids in turn with mercury, air, and water; for porous materials the voids are greatest for air, less for water, and least for mercury. The differences between the values are a measure of the porosity relative to the fluids employed. Several specimens of ore and sinter were examined. Ores are more porous than sinters, while the voids of mixtures are additive. It is shown how the measurements can be applied to forecast the behaviour of materials in the blast-furnace (deoxidation and carbon deposition).

Mr. O. I. Giniewski (Department of Biological and Colloidal Chemistry, The Hebrew University, Jerusalem) wrote: The authors have proposed a porosity test to forecast the working qualities of ores. Concerning this quality the authors' conclusion remains quite valid, but I will show in the following how the determination of the porosity, carried out as proposed by them, may lead to false interpretations. To avoid this it is proposed to modify the technique of porosity determination in accordance with the method elaborated by myself. My method not only gives more accurate porosity values independent of the fluid filling the pores of the porous bodies, but also has the advantage of being simpler.

(1) *The Penetration of Liquids into Porous Material.*—When studying the power of penetration of different liquids into porous matter I demonstrated * the existence of the following relation:

$$V = a - b.s \quad . \quad . \quad . \quad (1)$$

where V is the volume of liquid imbibed per gramme of matter (*i.e.*, filling the pores which communicate with the external surface) when the equilibrium state is reached, the porous matter being plunged in the liquid; s is the surface tension (dynes per centimetre) of the liquid in contact with air; and a and b are constants which depend on the nature of the porous material.

This relation has been checked for different materials, *e.g.*, fritted glass, graphite, fritted iron, cement, &c., with the aid of liquids like acetone, ethyl and methyl alcohol, benzene, water, &c.; it shows that, other factors remaining constant, the liquid is absorbed by the porous material more completely as the surface tension decreases. By this relation the real volume of the porous material can be calculated and a very accurate *porosity index* defined. One might assume that a hypothetical liquid of which the surface tension was zero (*i.e.*, $s = 0$) would completely fill all the pores of the material communicating with the external surface.

If in equation (1) s is made equal to zero, V becomes equal to a. *Thus the experimental coefficient* a *represents the total volume of the flores of the material.* Knowing a (experimentally determined), the density can easily be calculated.

(2) *Determination of* a.—The porous body is suspended from the beam of an analytical balance and plunged into the liquid, and the apparent weight, when equilibrium is established, is noted; the density of the liquid being known, V is easily calculated. By repeating the experiment with different liquids with differing surface-tensions, values for V can be obtained from which the curve $V = a - b.s$ can be drawn.

The real volume of the porous body (and consequently its density) is obtained by deducting the total volume of the pores (*i.e.*, the coefficient a) from the apparent volume (determined, for example, in mercury). The following are two examples:

A.—A piece of fritted glass is suspended in different liquids to determine the relevant equation of imbibition:

$$V = 0{\cdot}39 - 0{\cdot}0045s \text{ c.c.}$$

$$\text{Mass} = 1{\cdot}173 \text{ g.}$$

Apparent volume (in mercury) = 0·914 c.c.

From this the real volume is deduced:

$$0{\cdot}914 - 0{\cdot}39 = 0{\cdot}524 \text{ c.c.}$$

and the density:

$$\frac{1{\cdot}173}{0{\cdot}524} = 2{\cdot}24 \text{ g./c.c.}$$

B.—A determination on electrode graphite gave:

$$a = 0{\cdot}225.$$

$$\text{Mass} = 1{\cdot}56 \text{ g.}$$

Apparent volume (geometrical dimensions) = 0·93 c.c.

from which the density is found to be 2·45 g./c.c.

(3) *Determination of the Index of Porosity.*—With the help of two liquids of different surface tensions it would be possible to determine the imbibition line ($V = a - b.s$) relating to the body in question. Let curves (1) and (2) in Fig. A be such lines relating to two bodies, Nos. 1 and 2. It is clear that the porosity cannot be determined by the simple comparison of the volume of a liquid penetrating into Nos. 1 and 2, because it is possible (at least theoretically) that one imbibi-

* Thèse Doctorat Chimie, Montpellier, November, 1944.

tion line might intersect another (line x). In this case, material x happens to have a greater porous volume for liquids with a large surface tension, whereas No. 1 seems to be more porous when the comparison liquid has a small surface tension.

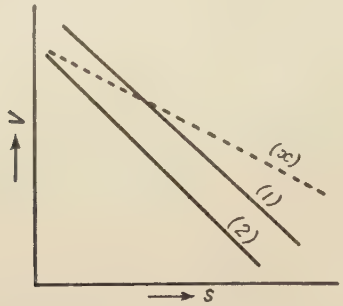


Fig. A.—Imbibition Lines.

In other words, the determination of the porosity of a material must be independent of the nature of the fluids which penetrate it, and the porosity should be defined only as a function of the characteristic coefficients of the porous solid as is shown in the following.

Equation (1) allows the fineness of the pores to be characterized. Let us consider a capillary tube of diameter $2r$ and of capacity v_0; let p be the initial pressure (1 atm.) of the gas contained initially in the capillary tube, P the pressure of this same gas when static equilibrium after immersion is reached, and v the volume thus occupied by the liquid. One can write:

$$P = v.p/(v_0 - v) \text{ and } P - p = v.p/(v_0 - v),$$

and at equilibrium:

$$2\pi rs.\cos\theta = 2\pi rI = (P - p)\pi r^2,$$

where I is the difference between the solid/gas and solid/liquid interfacial tensions and cos θ is the cosine of the angle of contact. Finally one obtains:

$$2s.\cos\theta = (P - p)r = vpr/(v_0 - v)$$

or

$$v/(v_0 - v) = V/(a - V).$$

Assuming that all the pores of the material have the same diameter we have:

$$2s.\cos\theta = 2.I = Vpr/(a - V).$$

Thus for the same material and the same liquid (same I and same total volume of the pores a) V varies inversely as r, *i.e.*, the coefficient b of equation (1) becomes smaller as r decreases. Thus b characterizes the fineness of the pores in the material.

(4) *Definition of the Index of Porosity.*—The index of porosity is defined by the relation b/a. The following are some numerical values:

	b/a
Fritted glass	0·0115
Electrode graphite	0·0126
Bricks	0·0117

(5) *Conclusion.*—I propose to use the index b/a for the evaluation of the porosity of ores and to introduce it into the "S.K." porosity test.

AUTHORS' REPLY.

The Authors wrote in reply: We cannot accept Mr. Giniewski's conclusion that liquid penetration is independent of vapour pressure and increases with lowered surface tension so that at zero surface tension the pores would be completely filled despite imprisoned air. The figures quoted do not differentiate between three materials of very different texture; moreover, gaseous reduction as in the blast-furnace cannot adequately be assessed by porosity measurements made with wetting liquids alone.

THE EFFECTS OF DIFFERENT METHODS OF PRE-TREATING IRON AND STEEL BEFORE PAINTING.

By F. FANCUTT, F.R.I.C., A.M.I.Chem.E.

(London, Midland and Scottish Railway Company, Derby).

Paper No. 17/1946 *of the Corrosion Committee* (*submitted by the Protective Coatings* (*Corrosion*) *Sub-Committee*).

This Report is published as Special Report No. 31; it was included in the programme of papers presented at the Annual General Meeting of The Iron and Steel Institute, held in London, at the Offices of the Institute, on 1st and 2nd May, 1946. The following is a synopsis of the Report.

Synopsis.

The dependence of the durability of paint applied to iron and steel upon the surface condition of the metal is strongly emphasized by the results of this investigation. All treatments tested which leave the steel surface in a rust-free, scale-free condition at the time of paint application are comparable in presenting an "ideal" surface for painting, and the choice between them will generally be determined on economic grounds or convenience of operation.

The simulataneous presence of rust and scale below a paint film induces rapid breakdown, while light surface rust in the absence of scale, though accelerating paint failure, is not so deleterious, especially where red lead paint is used in priming. Exposure of the descaled steel, unless accompanied by the formation of a visible film of rust, does not, however, shorten the life of paint subsequently applied.

The durability of paint applied to the as-rolled surface (*i.e.*, scale-bearing, but rust-free), provided that the film of scale is practically complete and unbroken, is much the same as for the scale-free, rust-free surface.

The rate of breakdown of paint applied to a clean, rust-free, scale-free surface appears to be mainly a function of the paint itself, and to be largely independent of (*a*) the type of steel, (*b*) the descaling method employed, *i.e.*, chemical or mechanical, (*c*) nature of acid used, (*d*) the presence or absence of inhibitors added to the pickling bath, and (*e*) the washing process employed after pickling.

The life of paint applied to a steel surface not in the ideal condition is, on the other hand, influenced by a number of factors, including (*a*) the type of steel, and (*b*) the nature of acid used, in addition to the sometimes overwhelming factor of surface condition.

The method of paint application is of importance when it influences the weight of paint applied, and in this investigation spray-applied films were heavier and consequently more durable than brushed ones. Red lead priming is much superior to red oxide on rusty surfaces, but the difference is less, and may even be reversed under certain conditions, when rust-free, scale-free surfaces are involved.

The First Hatfield Memorial Lecture.

THE SERVICES TO METALLURGY OF THE LATE DR. W. H. HATFIELD, F.R.S.

By GEORGE B. WATERHOUSE, Ph.D., D.Met.
(Professor of Metallurgy Emeritus of the Massachusetts Institute of Technology).

Synopsis.

The lecturer first reviews Dr. Hatfield's early life and training in Sheffield up to the time of his appointment as Director of the Brown-Firth Research Laboratories in 1916. *He held this appointment until his death* 27 *years later, and the main part of the lecture is devoted to a fuller account of his activities during this period. The wide range of subjects covered by his investigations, his attention to the organization of research, and his work for the Joint Research Committees of The Iron and Steel Institute and the British Iron and Steel Federation are dealt with in detail. The large number of papers in which he reported the results of his investigations are quoted as examples of his constant effort to promote the free exchange of metallurgical knowledge. In tracing Dr. Hatfield's life, the lecturer shows how his interests were at first restricted to a few plants, how they extended to others, and how they eventually spread beyond Great Britain to the other nations of the world.*

Members and guests of The Iron and Steel Institute; Fellows and Friends of the Royal Society; Alumni, Officials, and Students of the University of Sheffield:

It is a great honour to be invited to give the first annual Hatfield Memorial Lecture and to be able in this way to pay tribute to a great and distinguished metallurgist in the field of iron and steel.

Mr. Walter S. Tower, President of the American Iron and Steel Institute, wished me to read and present the following letter:

March 26*th*, 1946.

Officers, Directors, and Members of The Iron and Steel Institute:

Your invitation to our colleague, Dr. George B. Waterhouse, to deliver the first Hatfield Memorial Lecture on the occasion of your Annual Meeting is a compliment to him and to all the men of the steel industry in this country. And it is a welcome opportunity to reflect the high esteem for Dr. Hatfield so long held by our steel men.

Dr. Waterhouse has kindly consented to take our greetings to you on the occasion of that meeting. The preliminary programme which came to our notice indicates an interesting group of papers. You have our friendly greetings and very best wishes for a successful meeting.

It is especially pleasant to believe that your industry is now definitely on its way to recovery of completely peace-time status.

(*Signed*) Walter S. Tower,
President.

It is very fitting that this first lecture in memory of Dr. William Herbert Hatfield should be held during the Annual Meeting of The Iron and Steel Institute, because, as will be brought out later, he was a loyal and devoted Member of the Institute. For over forty years he took a great interest in its activities, believed whole-heartedly in its aims and objects, and contributed very largely to its success.

The Lecture Committee suggested that the subject of this first lecture might very properly be the contribution and influence of Dr. Hatfield's metallurgical work.

As the first step in this large undertaking it will be very helpful to point out briefly the main features of his metallurgical activities. For aid in this I am greatly indebted to the excellent obituary prepared by Dr. C. H. Desch, F.R.S.,[1] and to a memorandum from his fellow workers in the Brown-Firth Research Laboratories; I have also drawn upon my own recollections.

He was a native of Sheffield, and, as was perhaps natural, he became interested in the iron and steel industry and remained devoted to it all his life. While working as a young man in a steelworks laboratory he attended evening classes at the Sheffield Technical College, where he studied under J. O. Arnold, A. McWilliam, F. Ibbotson and F. K. Knowles. These men, all of them of great ability and strong character, had a great influence on him, as they had on all who attended their courses. He graduated and was awarded the highest honour, the Mappin Medal, in 1902, when only twenty years old. This is a striking evidence of his capacity for hard work and mental activity because this award was open to both day

and evening students and competition was intense.

For the next fourteen years he was connected with Messrs. John Crowley and Co., Ltd., as Metallurgist and Manager, and later as Director, and was greatly interested in steel castings, cast iron, and malleable cast iron. He continued his scientific studies and connection with the College, which during this period became a part of the newly created Sheffield University. In 1913 he received the degree of Doctor of Metallurgy. Also during this period, appeared the first of his very large number of papers dealing with iron and steel. There were seventeen, two of them on steelmaking in the acid open-hearth furnace, while the other fifteen were on cast iron and malleable cast iron. The first of the papers on cast iron appeared in the No. II. Volume of the *Journal of The Iron and Steel Institute for* 1906, and was his Carnegie Scholarship Report. Nine of these seventeen papers were judged worthy of publication in the *Journal*, evidence of the value of his scientific work.

In 1916 he was appointed Director of the Brown-Firth Research Laboratories in Sheffield, succeeding Mr. Harry Brearley, the discoverer of the cutlery type of stainless steel. This proved to be an ideal appointment; Hatfield found full scope for all his interest and activities and continued as Director until his death in October 1943. He further developed the laboratories and described them in 1928 as "a number of laboratories, chemical, physical, mechanical, corrosion, metallographic, pyrometric, heat-treatment, &c., each section having at its head a man particularly specializing upon his subject. Of the utmost importance is the free exchange of knowledge and ideas between the several sections since, although specialization is necessary, the general bearing of any work undertaken must never be lost to sight."

This "free exchange of knowledge and ideas" was characteristic of him, and with the full support of the Brown-Firth management he widened his activities in later years, and was one of the moving spirits in free exchange of metallurgical knowledge and advancement throughout Great Britain.

The two companies served by his research laboratories were merged in 1930 to form Messrs. Thos. Firth and John Brown, Ltd.,[2] and he later became a member of the Board of Directors. He was also a Director of one of the associated companies, Firth-Vickers Stainless Steels, Ltd., and maintained very close contact with the other subsidiaries, and with the associated American Company, the Firth-Sterling Steel Co. of Pittsburgh, Pa.

During the period 1916 to early in 1944 he published no less than 123 more papers. A brief digest of the subjects gives an indication of the work being done, and of the results he felt would be of value to others. Some deal with actual manufacture, such as one on steel castings and another on the manufacture and testing of steel forgings. Many of them deal with the application of the steels and special products made by Firth Brown's, such as: Automobile steels; steels for marine engineering; turbine steels; steels used in aero work; cutlery steels; double reduction gears for turbines; modern developments in special steels; stainless steels; rust-, acid-, and heat-resisting steels; steels for structural purposes; metals and alloys of the future (written in 1931); uses of nitride-hardened steels; drill steels for mining purposes; fabrication of articles from stainless steels; heavy forgings; steels for aircraft; heat-resisting steels.

Others of the papers deal particularly with the properties or peculiarities of such steels, for instance: Season cracking; mechanism of failure of metals under internal stress; permanence of dimensions under stress at elevated temperatures; the intercrystalline corrosion problem as observed in certain chromium–nickel corrosion-resisting steels; creep as occurring in steels under service conditions; non-metallic inclusions in steels; the damping capacity of engineering materials.

In 1928, Hatfield made one of his frequent visits to the United States, and at Philadelphia, in October, delivered the Campbell Memorial Lecture at the Tenth Annual Convention of the American Society for Steel Treating (now the American Society for Metals). His subject was "The Application of Science to the Steel Industry." It was amplified and published by the Society as a book[3] of 154 pages. It was sold at a reduced price and had wide distribution. Because of this, and the clear presentation of the various subjects, it had considerable influence on metallurgical thought and education in the United States. In connection with this lecture, Mr. William H. Eisenman, Secretary of the American Society for Metals, and its guiding spirit since its formation has asked me to present the following letter:

> It is given but to few men to make the contribution to metallurgy that was the share of Dr. Hatfield.
>
> He was one of the early members of the American Society for Metals and made his interest in its success a definite responsibility. He readily responded to the invitation to deliver the Edward De Mille Campbell Memorial Lecture in 1928. The masterful presentation of his interesting subject remained for years an inspiration to the American metallurgical profession.
>
> We, in America, shall always cherish the profound contributions and pleasant memory of Dr. Hatfield.

Before leaving this subject may I point out that a careful reading of this book is very valuable, even to-day, almost twenty years after its presentation. Also, it gives a clear idea of Hatfield's views on the metallurgy of iron and steel, and his approach to its problems, together with the wide scope of his thinking and activities.

Beginning with 1929 an increasing number of his papers dealt with steel ingots, with corrosion, and with research as regards alloy steels. These were essentially reports on the work of important Committees in which Hatfield was interested.

Mention must be made of these Committees, because no discussion of Hatfield's work or its influence on metallurgy would be complete without regard to them and the important results obtained. For complete detail reference must be made to *Special Report No.* 29 of The Iron and Steel Institute,[4] a book of 175 pages, published in 1943. It was originally prepared by Hatfield, and various members who worked on individual sections, and was revised by Mr. K. Headlam-Morley, Secretary of the Institute.

There are four main committees: The Committee on the Heterogeneity of Steel Ingots, formed in 1924 as an offshoot of a previous committee started in 1917; the Corrosion Committee, formed in 1928; the Alloy Steels Research Committee, formed in 1934; and the Steel Castings Research Committee, formed in 1934. The account of the formation and close relationship of these Committees given in the Report is of great interest, but we are concerned chiefly with the manifold activities of Hatfield in this respect. He was Chairman from the beginning of the first three, namely, those on ingots, corrosion, and alloy steels, and of important Sub-Committees such as those on non-metallic inclusions, on hair-line cracks and on special aero components. In addition he was a member of the Committee on Steel Castings and of many other sub-committees. These Chairmanships he held until his death, and he considered this work of the greatest importance.

The results obtained by the efforts of the 170 or more members of these various Committees and Sub-Committees will be gone into later, but at this time it can be said that they have proved to be of enormous value to steel men throughout the world, and everyone concerned deserves the commendation and gratitude of the entire industry.

The mention previously made of Hatfield's published papers, namely, 140, should be increased to include the Reports of the three main Committees of which he was Chairman. For instance nine Reports have appeared on the work on steel ingots, many of them books in themselves, such as the Eighth Report in 1939 of 322 pages. The Corrosion Committee has issued five Reports, the last one being of 448 pages, and the Alloy Steels Committee has issued two, the last one of 390 pages. All of these were carefully edited by him and must have required a vast amount of time and effort.

This may not be the place to speak of his activities during the war, and yet no picture of his life would be complete without this being done. Late in August 1938, I spent a little time with him in Sheffield. He seemed to feel then that war was inevitable and that the steel men would have to organize and engage in still closer co-operative work to meet the problems that would come up. Needless to say he did his full share from the beginning in the great task laid on technical men during the war. May I quote a short paragraph from the excellent obituary published by The Iron and Steel Institute in 1943.[5]

> A full account of Dr. Hatfield's war-time activities cannot be given at the present time, but it can be said that he was largely responsible for convincing the authorities that, in spite of the concentration of effort on increased iron and steel production, it was necessary for research work to continue. He served on several committees set up to deal with problems connected with the war, a very important one being the Technical Advisory Committee on Special and Alloy Steels, of which he was Chairman. Together with a group of well-informed metallurgists and representatives of Service Departments, this committee undertook a revision and rationalization of the innumerable specifications for special and alloy steels, which resulted in the issue of the "En" series of specifications, reducing the number from 3000 to 83. In addition, he was Chairman of a series of Technical Committees on Armour, of the Technical Committee advising the Iron and Steel Control, and of a small committee responsible for the examination of enemy-aircraft and other components.

In the spring of 1942 I spent a number of weeks in Great Britain, making my headquarters at London, but also being at the main office of the Iron and Steel Control at Ashorne Hill, and also at branch offices at Sheffield and Birmingham. While at Sheffield I was privileged, under the guidance of Major E. W. Senior, to attend a meeting of the Technical Committee on Special and Alloy Steels, held in the well-known conference room of the Brown-Firth Research Laboratories, and presided over by Dr. Hatfield. Later in the day I was given a full set of the "En" specifications covering special steels, and was allowed to read the minutes of many of the meetings of the Committee. I can testify as to the great importance and value of the work done, its efficiency, and the devotion of both the

Chairman and the members to the innumerable details of their work.

Another day I attended a similar meeting of the Committee on Armour and later, at Ashorne Hill, at Sheffield, and at Glasgow, went thoroughly into the details of the important work of this group. During my stay in England it was possible to cover many other phases of the war activities of Hatfield and his associates, and to spend a good deal of time with him and with them. All of his organizing abilities, his fondness for research and development work, and his liking for co-operative and committee work were used to the utmost, with results that were of the greatest value to the war effort.

Again in March 1943, I was able to spend some time with him when he was a member of the distinguished group of Metallurgists under Mr. C. R. Wheeler, who came to consult with us regarding mutual problems. Together with others of the group he showed very clearly the strain of the heavy work he was carrying, intensified by a rough and hazardous crossing. As you all know, soon after his return to England he became ill, and passed away in October of that same year.

This very brief review gives an idea of his many activities along metallurgical lines, and will serve as a background against which to point out his influence on the metallurgy of iron and steel.

In the first place was the work he did on acid open-hearth steelmaking. It was a forerunner of the development generally called the physical chemistry of steelmaking. One of the most important parts of this work is the importance of slag composition, of temperature, and of the interrelation of molten metal and slag. All these were clearly indicated in these early papers by McWilliam and Hatfield. They clearly showed the great importance of thorough deoxidation of the steel bath, and pointed out that one agent in this important operation was the silicon reduced into the steel from the acid slag under certain conditions.

Hatfield seemed always to distrust basic open-hearth steel, at least for many of the uses in which he became intensely interested as time went on, and the main reason seemed to be his belief that it could not be thoroughly deöxidized, and that the final product would not be as sound or clean as well-made acid open-hearth or electric-furnace steel. His work created great interest at the time and in succeeding years in acid open-hearth practice which, though declining in tonnage output as years have gone on, is still an important method of steelmaking for castings, for armour plate, and for special steels.

His work on cast iron had a marked and important influence. It pointed out the part that research can play in this important field of metallurgy. His book [6] was one of the pioneers in what has proven to be a very prolific field of literature. When he commenced his work even a chemist was practically unknown in an iron foundry. Irons were bought and sold on grade and fracture, and fracture was the basis of foundry mixtures.

The metallurgy of cast iron is now fairly well understood. We produce cast irons for many various purposes, not just as a cheap material to use in columns, and engine frames, and in places where weight and resistance to compression are needed.

We know that cast iron is a most interesting material or series of materials. From one point of view it is steel plus graphite. The properties of the steel can be varied according to the amount of combined carbon it contains, the alloys used, and the heat-treatment. The influence of the graphite varies according to its amount, its distribution, and the size and shape of the graphite flakes. In addition there is the important group of cast irons with a hard chilled surface or outer layer, and an interior consisting of the steel-plus-graphite combination. The control of many of these various structures and combinations is now well understood, and we find cast iron used for such diverse things as Diesel engine crankshafts, piston rings, cylinder blocks and liners, water and sewer pipe, rolls, steam and hot-water radiators, freight- and mine-car wheels, engine and motor bases, and a host of other things, such as diverse castings used in automobiles, trucks, agricultural machinery, and in general industry.

As a direct consequence of these many applications, and the need for uniform quality, every well-appointed foundry has a metallurgist and a well-equipped laboratory to put into application the findings of research, and all these people rely on the work of pioneers such as Hatfield.

Without any question many of the Hatfield Memorial Lecturers, as time goes on, will take as their subject something connected with cast iron or malleable cast iron, and trace in greater detail than I have even attempted, the direct descent of their work from that of Hatfield. My own copy of his book on cast iron had been loaned to a foundry metallurgist some years ago and never returned, and I asked one of our prominent foundry men to lend me his copy a few weeks ago and found that this had happened to him also. He confirmed my own opinion that this book was one of the corner stones of knowledge on which foundry metallurgy is built.

Beginning in 1916, Hatfield devoted his time to expanding the work of the Brown-Firth Research Laboratories, and helping to solve the problems of Messrs. Thos. Firth and John Brown,

Ltd., and their associated companies, in regard to steelmaking and particularly steel applications. This included especially the field of alloy steels. He and his associates, working under his direction, had a great influence in the field of the corrosion-resistant steels, and there seems to be no question that he pointed out the excellence of the steel he called "Staybrite" and which the world calls 18–8. In many ways it was natural. Brearley had discovered the cutlery type of stainless steel which owes its qualities to chromium and to careful heat-treatment. Hatfield succeeded him in the Brown-Firth Laboratories and undoubtedly took this as a starting point, experimenting with additions of chromium, nickel, and other alloying elements. Having settled on a composition that had a combination of many excellent properties, many other problems immediately arose, such as the behaviour of this steel when exposed to many conditions of temperature, various solutions and atmospheres. Also the queer failure of this steel under certain conditions which became known as intercrystalline corrosion. By means of the large number of carefully controlled experiments carried out and his well documented publications, Hatfield had a great influence on the wide and successful application of, not only 18–8, but a number of other distinct types of stainless steel, and also played a great part in working out the remedy for the dangerous failure by intercrystalline corrosion. A typical development was the working out of an accelerated test to discover whether an 18–8 or other steel would be subject to this type of failure, and this also was fully described and became very widely used.

In addition to the corrosion-resistant steels, work was carried on with heat- and scale-resisting steels, steels to withstand creep at ordinary and high temperatures, and with studies on damping capacity. Creep tests take a very long time to work out, and Hatfield developed an accelerated test which has proved to be of value.

His interest and influence in regard to alloy steels and corrosion continued until his death, both in the work in his own laboratories, his publications, and particularly in his work with the Committees on Corrosion and on Alloy steels.

The important work of the Corrosion Committee and its Sub-Committees has been felt everywhere. It is somewhat different to the other groups in that from the beginning it has employed a special staff and has maintained laboratories. It has not concerned itself with the stainless and non-corrosive steels alone, but has continuously and extensively investigated the corrosion of ordinary steels, of wrought iron, and of the low-alloy steels; also the effects of paints and protective coatings, and anti-fouling compounds, and marine corrosion and the corrosion of buried metals. The theoretical and laboratory studies carried out at Cambridge University under Dr. U. R. Evans and his associates are followed with great interest and have been of great value.

The work of the Alloy Steels Research Committee is fully supported by the leading alloy-steel producers in Great Britain. One Sub-Committee devotes itself to the subject of gases in steel, and has received international support in the search for standard or accepted methods of analysis. Another important Sub-Committee is occupied with the important subject of hair-line cracks in forgings and in steel generally, often referred to as snow-flake fractures—their cause and particularly their prevention.

The reports and the papers published by the Committee on Alloy Steels have been followed with the greatest interest and the earnest members may rest assured that their work has been and is of great importance.

There may be a question as to which Committee and which main subject has contributed most to metallurgical knowledge in the iron and steel field. All have been most helpful. My own preference is the work on steel ingots, the Committee being known by the title "The Committee on the Heterogeneity of Steel Ingots." Perhaps this is because I have had to devote many years to some of the subjects covered. For instance some years ago I spent much effort and time on the preparation of standard analytical samples, which work is now carried on by the National Bureau of Standards at Washington. Then, like all steel men, I have had to study the structure and soundness and uniformity of ingots, and have sectioned and examined a great many different kinds of ingots. Then, further, for many years I was engaged in the manufacture of ingot moulds and had to follow the influence of composition of metal, of methods of production and of design on their life, and their effect on the steel ingots produced.

Apparently the work of this group, the oldest of the Committees, grew out of the preparation of standard samples for use in chemical analysis, with which work Hatfield was associated. It soon became evident that to obtain uniform samples was a most difficult task because of the non-uniformity of steel ingots. The Committee was formed at the suggestion of a former Bessemer Medallist, Mr. E. H. Saniter. Many years ago I remember Saniter telling me of one of his experiences. He was engaged in the manufacture of seamless steel tubes and, knowing the excellence of certain Swedish products, obtained a number of ingots from the particular Swedish plant in question. These he cut up and sectioned in various ways, examined them thoroughly by analysis, by etching in acid and other ways, and then worked out his steelmaking practice to reproduce those particular ingots as closely as

possible, with the final result that seamless tubes made from those ingots met every test and were successful. With such a background I can imagine how much in earnest Saniter was in proposing that a thorough study be made of the influence of ingot moulds and other causes on the uniformity or heterogeneity of steel ingots. Hatfield was unanimously chosen as Chairman in May 1924, and continued as Chairman until his death.

The results of the work of this committee have been followed with the closest interest by steelmakers everywhere. In 1939 Hatfield described [4] the work as follows : " Work was begun on killed carbon-steel ingots, but it was soon extended to include other carbon-steel ingots, namely, those of balanced and rimming steel, as well as ingots of alloy steels. At an early date it was found necessary to give consideration also to ingot moulds, and to pyrometry, to the determination and effect of oxygen and other gases, and to analytical methods.

A number of special investigations were authorized, including mathematical studies and numerous theoretical enquiries into the mechanism of freezing." Also, in another place,[4] " The Ingots Committee is concerned primarily with the study of steel ingots and with the occurrence and causes of segregation and of non-metallic inclusions."

Six Sub-Committees have been set up on the following subjects : Ingot Moulds, Physical Chemistry of Steel Making, Liquid-Steel Temperatures, Gases in Steel, Inclusions in Steel, and Standard Methods of Analysis.

The work of the Committee has therefore covered an enormous field. Almost 100 ingots have now been cut up and examined, ranging in weight from about ½ ton to over 170 tons. All kinds of ingots were included—top-poured and bottom-poured, in wide-end-up moulds, and ordinary moulds, with hot tops and without, fluted moulds, and smooth moulds, from all kinds of steelmaking methods, and all kinds of steel, including killed steel, rimming steel, forging steels, and free-machining steels. In practically every case the steelmaking practice was carefully observed. Some ingots were poured fast, some slowly; some from hot steel, some on the cold side.

As a result, a body of knowledge has been built up that is enormous and of the greatest value, and fully described in splendid reports. In addition this work has inspired similar studies by individual workers in separate steel plants, or theoretical studies in laboratories or universities, so that our knowledge of this most important part of steelmaking practice has been tremendously advanced.

There is a great temptation to go into detail on the work of these three main Committees and Sub-Committees, but that temptation must be resisted. Suffice it to say that under the inspiring leadership of the various Chairmen, among whom Dr. Hatfield, and his enthusiastic fellow worker Dr. T. Swinden, must be singled out for special mention, the work never flagged from the beginning, but reached new heights of achievement with the passing of time; and was put on such a firm and secure basis that the death of these two great workers, and others, and even the great war, could not interfere with success and continued progress.

As requested by the Lecture Committee, the preceding pages have endeavoured to indicate the activities and influence of Dr. Hatfield along metallurgical lines. It will be noticed that, at the beginning, these were in connection with acid open-hearth steelmaking and with foundry metallurgy and practice. Then, at about the age of 35, the emphasis began to be placed on high-grade and alloy steels, both their manufacture and particularly their properties and applications. His interests at first were restricted to a few plants, then gradually spread to others, until towards the end not only Great Britain came within his scope, but in many cases the interests of the world.

Thus in having traced these activities, I feel I have covered, in a brief manner, the suggestion of the Lecture Committee, and for the few minutes remaining would like to depart a little from this viewpoint. His life and activities constitute a book with many well-filled pages. Like all engineer's books, there are many diagrams and charts and illustrations, together with carefully written paragraphs and conclusions. The leaves have to be turned carefully and the pages studied in order to learn all the lessons.

Ever since the first cable arrived from London a few weeks ago I have been thinking of Hatfield, a man whose career I have been in touch with for about forty years, and whose life I have followed with much interest. The question immediately arises : What made him act as he did, what were his " springs of action," as Shakespeare says ?

It is impossible to answer this fully, but I would like to make the attempt. During his formative years, like all of us, he was developing, consciously or not, a philosophy of life. During this period the motives for his actions were being formed. As time went on we see these motives and this philosophy in action. As with all good workmen, they consisted partly in the love of a task or a job well done. I am sure he delighted in the conception of a piece of research, in carefully planning the approach to the question, the line of attack, the experiments to be carried out. Then, as the answer became evident, in describing

these experiments and the results so that others could share in the work, and be helped and encouraged in regard to their own problems. At first he thought principally of the problems of his own plants, and the customers and users of the products of those plants. Then as time went on the opportunities available to him, particularly the Research Committees, made it possible to consider the problems of others. To these problems he brought the use of all the tools God had given him, the love of study, idealism, a marvellous memory, the ability to work with and influence other men. All of these tools he kept bright and keen, and with continued use they became ever more effective.

I feel sure that among his ruling motives was a just and proper ambition to succeed in whatever task he undertook, a love for rewards for work well done, such as his well-deserved Degree from his University, his Fellowship in the Royal Society, his award of the Bessemer Medal; and without any doubt I know one of his strongest motives was to carry out as far as he could the teachings of the Golden Rule, which is as needed in engineering as it is in religion.

And so we see Hatfield developing as the years went on so that when his great task presented itself he was ready. His interests and his influence covered his beloved country. No change of attitude or of motive was needed. Each demand found him ready and when his appointed time arrived he never flinched, but went to his grave, and to his reward, as any of the brave heroes of old.

REFERENCES.

1. C. H. Desch: "William Herbert Hatfield, 1882–1943." *Obituary Notices of Fellows of the Royal Society*, 1944, vol. 4, p. 617.
2. "One Hundred Years in Steel" (Centenary on Messrs. Thos. Firth and John Brown, Ltd.) Sheffield, 1937.
3. W. H. Hatfield: "The Application of Science to the Steel Industry." Cleveland, Ohio, 1929: American Society for Metals.
4. "Review of the Work of the Joint Research Committees, 1924–1943." *The Iron and Steel Institute*, 1943, *Special Report No.* 29.
5. *Journal of The Iron and Steel Institute*, 1943, No. II., p. 721 P.
6. W. H. Hatfield: "Cast Iron in the Light of Recent Research." London, 1928: Charles Griffin and Co., Ltd.

The First Hatfield Memorial Lecture was delivered at The Institution of Civil Engineers, Great George Street, London, by Dr. George B. Waterhouse, Professor Emeritus of the Massachusetts Institute of Technology, on Wednesday, May 1, 1946, at 8.30 P.M. Dr. C. H. Desch, F.R.S., President of The Iron and Steel Institute, occupied the Chair.

The Hatfield Memorial Lectures.

Under a Deed dated 22nd August, 1944, the University of Sheffield agreed to be the Trustees of the fund which had been subscribed "for the purpose of establishing a lecture on the subject of Metallurgy, or some other subject connected therewith, as a Memorial to the late Doctor William Herbert Hatfield, Fellow of the Royal Society, and as a mark of appreciation of his distinguished work in connection with research into the qualities and uses of metals and allied branches of science." The lectures are to be known as the "Hatfield Memorial Lectures."

The lecturer is appointed by Sheffield University on the recommendation of a Lecture Committee, consisting of representatives of the University, the Royal Society, and The Iron and Steel Institute. At the discretion of the University the lectures may be published by The Iron and Steel Institute or by other publishers.

The late Dr. W. H. Hatfield, F.R.S.

(Born 1882; died 17th October, 1943)

William Herbert Hatfield studied Metallurgy at University College, now the University, Sheffield, under Professor J. O. Arnold; in 1902 won the Mappin Medal, received a grant from the Andrew Carnegie Research Fund to study carbon in cast iron, and presented, with Professor A. McWilliam, his first paper to The Iron and Steel Institute on the "Elimination of Silicon in the Acid Open-Hearth Furnace"; in 1913 obtained the degree of D.Met. of Sheffield. Author of numerous technical papers on many branches of metallurgy, particularly rust-, acid- and heat-resisting steels and of "Cast Iron in the Light of Recent Research" (1912).

Industrial experience with Sir Henry Bessemer & Co., Ltd., and Messrs. J. Crowley & Co.; in 1916 appointed Director of the Brown-Firth Research Laboratories, later also joining the Boards of Messrs. Thos. Firth and John Brown, Ltd., and its subsidiaries.

Chairman of the Heterogeniety of Steel Ingots, Corrosion, and Alloy Steels Research Committees of The Iron and Steel Institute, the Programme and Finance Committee of the Iron and Steel Industrial Research Council, the Technical Advisory Committee on Special and Alloy Steels, &c., to the Iron and Steel Control; Member of a Metallurgical Mission to America in 1942.

Associated with many technical societies; a Founder and first President of the Sheffield Metallurgical Association, President of the Sheffield Society of Engineers and Metallurgists; Member of Council of Sheffield University, Fellow of the Chemical Society, Institute of Physics, Institution of Chemical Engineers; Member of the Institution of Mechanical Engineers; in 1935 elected a Fellow of the Royal Society.

In 1928, delivered the Campbell Memorial Lecture of the American Society for Metals, and in 1938 gave the Tenth Gluckstein Memorial Lecture to the Royal Institute of Chemistry in London; awarded the Compton Medal of the Institution of Automobile Engineers.

Member of The Iron and Steel Institute in 1903, Member of Council in 1927, Bessemer Medallist 1933, Vice-President in 1934.

Dr. George B. Waterhouse.

George Booker Waterhouse was born in Sheffield in 1883; B.Met. at the University in 1901. After post-graduate studies went in 1903 to U.S.A.; studied under Professors H. M. Howe and Bradley Stoughton at Columbia University where he gained his Ph.D. degree in 1907; D.Met. of Sheffield University in 1937.

Naturalized an American in 1910; served with the Lackawanna Steel Co. as metallurgical and inspecting engineer; 1933 appointed Professor of Metallurgy at Massachusetts Institute of Technology, Cambridge, Mass.; Professor Emeritus in December, 1945.

In 1934, 1936, and 1937 was Chairman of the Board of Belmont (Mass.) School Committee. War service included Staff Consultant to the Office of Production Management (June, 1941, to December, 1942), Steel Division of the War Production Board (December, 1941, to August, 1942), Office of Lend-Lease Administration (August, 1942, to December, 1944) and Foreign Economics Administration (December, 1944, to May, 1945).

Was or is a Member of the Research Advisory Board of the Westinghouse Electric and Manufacturing Co., a Director of the Belmont Trust Co., Consulting Engineer to the U.S. Bureau of Mines, Chairman of the Metallurgy Advisory Commission of the U.S. Bureau of Standards, and Chairman of the Alloys of Iron Research of the Engineering Foundation.

Is a Member of the American Iron and Steel Institute, American Institute of Mining and Metallurgical Engineers (Chairman of the Iron and Steel Division in 1929, and a Director from 1933 to 1939), the American Society for Testing Materials, the American Society for Metals (Trustee since 1934 and President in 1937–38) and the American Foundrymen's Association; The Iron and Steel Institute, The Institute of Metals and the Cleveland Institution of Engineers; author of numerous scientific papers.

SECTION II.

A SURVEY OF LITERATURE ON THE MANUFACTURE AND PROPERTIES OF IRON AND STEEL, AND KINDRED SUBJECTS.

CONTENTS.

Abstractors and Translators: Mr. R. A. Ronnebeck and Dr. D. R. Steiner.

MINERAL RESOURCES

The World's Supplies of Iron. R. Durrer. (Schweizer Archiv, 1945, vol. 11, Aug., pp. 237–238). The distribution of iron ores throughout the world is briefly reviewed. At the present time the world production of iron is about 130×10^6 tons from about twice that quantity of ore. It can be said that the iron-bearing minerals of the world which are to-day regarded as ores are probably sufficient to last several hundred years and that the quantity of iron in the earth's crust is practically unlimited.

Manganese in Industry. L. L. Fermor. (William Menelaus Memorial Lecture: Proceedings of the South Wales Institute of Engineers, 1945, vol. 61, Nov., pp. 28–46). The world's manganese ore resources and their application are discussed under the headings: Mineralogy, Geology, Mining, Metallurgy, and Utilization.

Tin and Tungsten Deposits at Silver Hill, Spokane County, Washington. L. R. Page. (United States Geological Survey, 1942, Bulletin 931-H).

Tungsten Deposits of the Nightingale District, Pershing County, Nevada. W. C. Smith and P. W. Guild. (United States Department of the Interior, Geological Survey, 1942, Bulletin 936-B).

The Rose Creek Tungsten Mine, Pershing County, Nevada. R. J. Roberts. (United States Geological Survey, 1943, Bulletin 940-A).

Tungsten Deposits in the Boriana District and the Aquarius Range, Mohave County, Arizona. S. W. Hobbs. (United States Geological Survey, 1944, Bulletin 940-I).

Tungsten Deposits, Isla de Pinos, Cuba. L. R. Page and J. F. McAllister. (United States Geological Survey, 1944, Bulletin 935-D).

Tin Deposits of the Republic of Mexico. W. F. Foshag and C. Fries, jun. (United States Geological Survey, 1942, Bulletin 935-C).

Tin Deposits of Irish Creek, Virginia. A. H. Koschmann, J. J. Glass, and J. S. Vhay. (United States Geological Survey, 1942, Bulletin 936-K).

Vanadium Deposits of Colorado and Utah. R. P. Fischer. (United States Geological Survey, 1942, Bulletin 936-P).

Manganese Resources of the Olympic Peninsula, Washington. C. F. Park, jun. (United States Geological Survey, 1942, Bulletin 931-R).

Manganese Deposits in the Paymaster Mining District, Imperial County, California. J. B. Hadley. (United States Geological Survey, 1942, Bulletin 931-S).

Manganese Deposits of Cuba. C. F. Park, jun. (United States Geological Survey, 1942, Bulletin 935-B).

Manganese Deposits of Cedar Creek Valley, Frederick and Shenandoah Counties, Virginia. W. H. Monroe. (United States Geological Survey, 1942, Bulletin 936-E).

The Three Kids Manganese District, Clark County, Nevada. C. B. Hunt, V. E. McKelvey, and J. H. Wiese. (United States Geological Survey, 1942, Bulletin 936-L).

Manganese Deposits of the Elkton Area, Virginia. P. B. King. (United States Geological Survey, 1943, Bulletin 940-B).

Occurrence of Manganese in Eastern Aroostook County, Maine. W. S. White. (United States Geological Survey, 1943, Bulletin 940-E).

Manganese Deposits of the Lyndhurst-Vesuvius District, Augusta and Rockbridge Counties, Virginia. M. M. Knechtel. (United States Geological Survey, Bulletin 940-F).

Manganese Deposits in Part of the Sierra Maestra, Cuba. C. F. Park, jun., and M. W. Cox. (United States Geological Survey, 1944, Bulletin 935-F).

Geology and Manganese Deposits of Guisa–Los Negros Area, Oriente Province, Cuba. W. P. Woodring and S. N. Daviess. (United States Geological Survey, 1944, Bulletin 935-G).

Manganese Deposits in Costa Rica. R. J. Roberts. (United States Geological Survey, 1944, Bulletin 935-H).

Manganese Deposits in the Artillery Mountains Region, Mohave County, Arizona. S. G. Lasky and B. N. Webber. (United States Geological Survey, 1944, Bulletin 936-R).

Manganese Deposits of the Sweet Springs District, West Virginia and Virginia. H. S. Ladd. (United States Geological Survey, 1944, Bulletin 940-G).

Manganese Deposits of the Flat Top and Round Mountain Districts, Bland and Giles Counties, Virginia. H. S. Ladd and F. W. Stead. (United States Geological Survey, 1944, Bulletin 940-H).

Cobalt-Bearing Manganese Deposits of Alabama, Georgia and Tennessee. W. G. Pierce. (United States Geological Survey, 1944, Bulletin 940-J).

Vanadium-Bearing Magnetite-Ilmenite Deposits near Lake Sanford, Essex County, New York. J. R. Balsley, jun. (United States Geological Survey, 1943, Bulletin 940-D).

Chrome Resources of Cuba. T. P. Thayer. (United States Geological Survey, 1942, Bulletin 935-A).

Chromite and Quicksilver Deposits of the Del Puerto Area, Stanislaus County, California. H. E. Hawkes, jun., F. G. Wells, and D. P. Wheeler, jun. (United States Geological Survey, 1942, Bulletin 936-D).

Chromite Deposits near San Luis Obispo, San Luis Obispo County, California. C. T. Smith and A. B. Griggs. (United States Geological Survey, 1944, Bulletin 945-B).

FUEL

The Evaluation of Commerical Fuel Gases on the Basis of Their Combustion Properties. H. Schwiedessen. (Archiv für das Eisenhüttenwesen, 1942, vol. 16, Nov., pp. 167–172). Methods of calculating and comparing efficiency factors for coke-oven gas, producer gas, and blast-furnace gas are explained and discussed with practical examples of their application.

The Theoretical Heat Consumption of the Industrial Furnace in Relation to the Load and the Throughput. H. Schwiedessen. (Archiv für das Eisenhüttenwesen, 1944, vol. 18, Sept.-Oct., pp. 43–46). The factors affecting the heat consumption of industrial furnaces are discussed, and methods of determining the theoretical and actual consumptions are described with examples.

Consumption of Fuel in Iron- and Steelmaking. J. Durand. (Revue de Métallurgie, Mémoires, 1942, vol. 39, Oct., pp. 289–294). Data are presented and discussed on the consumption of fuel in the production of pig-iron, open-hearth and electric-furnace steels, and in forging and rolling. In conclusion it is stated that the main points to consider while aiming at the best possible utilization and economy of fuel are: (1) The continuation of heating operations without unnecessary interruptions, and (2) the choice of a proper furnace, equipped with adequate metering and controlling apparatus.

Treatment of Fines in Coal-Washing. W. Green. (Year-Book of the Coke Oven Managers' Association, 1945, pp. 71–76). The coal-washing system adopted by Manvers Main Colleries, Ltd., is described with special reference to the treatment of the fines. The fines are drawn from the conical tank of the Baum washer and treated in two stages, the first being a thickening process, whilst the second consists of treatment on a drum filter.

The Modern Preparation of Coal. R. Maxwell. (Year-Book of the Coke Oven Managers' Association, 1945, pp. 81–97). The de Vooys and Tromp methods of coal-washing and experience gained in the Tromp process for the density washing of coal above $\frac{1}{4}$ in. and in the treatment of dedusted fine coal below $\frac{1}{4}$ in. by the Rheolaveur process are described.

Some Trends in Coke-Oven Design. D. T. Barritt and R. J. Barritt. (Year-Book of the Coke Oven Managers' Association, 1945, pp. 109–123). New designs and ideas relating to the probable lines of post-war development in coke-oven plant are presented and discussed.

The Reactions of an Engineer to Modern Coke-Oven Practice. G. G. Owen. (Year-Book of the Coke Oven Managers' Association, 1945, pp. 174–197). A detailed survey is made of the more important forms of failure and repair work carried out at the Billingham coke-oven plant and at other batteries. The probable causes of failure are outlined and suggestions are made for improvements in design that will minimize or eliminate them.

The Preparation of Coke-Oven Gas for the District. W. S. Matthews. (Year-Book of the Coke Oven Managers' Association, 1945, pp. 214–222). It is expected that the number of coke-oven plants undertaking the purification of the surplus gas supplied for towns' use will materially increase; details are therefore given of experiences in supplying gas to specification.

Differences between By-Product Recovery Plant and Practice at Coke Oven Works and Gas Works. R. J. S. Thompson. (Year-Book of the Coke Oven Managers' Association, 1945, pp. 223–239).

Organisation and a Costing System for Coke Oven Plants. T. R. Harrop. (Year-Book of the Coke Oven Managers' Association, 1945, pp. 164–171).

Modern Metallurgical Gas Producers. F. Reddet. (Revue de Métallurgie, Mémoires, 1942, vol. 39, May, pp. 129–140). Details are given of a modern gas producer with water-jacket and gas-cleaning equipment. The utilization of peat and lignite for gas producers, and the inspection and tests of a gas-producer installation are also discussed.

PRODUCTION OF IRON

Sulphur in Pig Iron. M. Grison. (Revue de Métallurgie, Mémoires, 1942, vol. 39, Jan., pp. 1–11). After a brief description of various methods of desulphurizing pig-iron, the results are discussed of observations made during fourteen months in the ironworks at Longwy, where sodium carbonate was used for this purpose. The conclusions drawn are: (1) For pig-irons of the same sulphur content, the desulphurization with sodium carbonate seems to be more efficient in the blast-furnace than in the mixer; (2) the drop in the temperature of the molten iron caused by the sodium carbonate is insignificant, and has no ill effect; (3) a mixture of sodium carbonate, fluorspar and limestone forms a more active desulphurizing agent than the carbonate by itself; and (4) attention should be paid to the effect which the iron and slag with a higher silicon content have on the blast-furnace lining.

The Equilibrium Between Iron and Hydrogen Sulphide. E. Maurer, G. Hammer, and H. Möbius. (Archiv für das Eisenhüttenwesen, 1942, vol. 16, Nov., pp. 159–165). The equilibrium of the reaction $Fe + H_2S \rightleftharpoons FeS + H_2$ was studied by experiments in which mixtures of different proportions of iron-sulphide powder and pure iron were heated to temperatures in the 860–1530° C. range and hydrogen was passed over them. It was found necessary to have at least 95% of hydrogen in the initial gas in order to keep the decomposition of the hydrogen sulphide below 10%. Curves for the equilibrium constants at different temperatures in the above range are, after a slight initial rise, horizontal between

6% and 26% sulphur; from 26% to 36% sulphur the curves rise steeply. During the initial rise up to 4% sulphur the law of mass action applied, but not at higher proportions of sulphur. The experimental results are compared with those of J. Chipman and Ta Li (*see* Journ. I. and S.I., 1937, No. I., p. 14 A).

The Compressive Strength and Specific Gravity of Light Concrete Made from Foamed Slag. F. Keil and F. Gille. (Archiv für das Eisenhüttenwesen, 1942, vol. 16, Nov., pp. 153–157). Data on the specific gravity and mechanical properties of concrete made from mixes of foamed slag and sand are presented and discussed.

The Knowledge of Slags—Basis of Metallurgy. F. Körber and W. Oelsen. (Revue de Métallurgie, Mémoires, 1942, vol. 39, July, pp. 211–217). An abridged French translation is given of a report published in Stahl und Eisen, 1940, vol. 60, Oct. 17, pp. 921–929, and Oct. 24, pp. 948–955, dealing with the investigation of slags on the basis of equilibrium diagrams. (*See* Journ. I. and S.I., 1942, No. I., p. 7 A; and Translation Series, No. 74).

Reduction of Iron Ore in Clay and Steel Containers (Saggers). J. P. Walker. (United States Bureau of Mines, 1945, Sept., Report of Investigation No. 3819). Tests to determine the metallurgical factors involved in making sponge iron from "ceramic hematite" in clay crucibles (called "saggers") are described. Two types of coke breeze and two bituminous coals were used as reducing agents and two types of lime and three of limestone were used as desulphurizing agents. At 1750° F. the reducing time was about twice that required at 1950° F. The cooling down of the sponge iron to the temperature at which it ceases to oxidize should be as rapid as possible. When the ore and the reducing agent were well mixed the time for reduction was about half that needed when the materials were charged in layers. Limestone was a more effective desulphurizing agent than hydrated lime or quicklime.

Production of Sponge Iron in a Shale-Brick Plant. D. W. Ross. (United States Bureau of Mines, 1945, Sept., Report of Investigations, No. 3822). Sponge iron in shaped masses similar to the two types made at a ceramic plant in Sweden can be produced with carbon as the reducing agent in an ordinary shale-brick plant. American magnetites, hematites, limonites and mill-scale can readily be reduced to sponge iron in "saggers" (*see* preceding abstract) in tunnel kilns built to operate at up to 1150° C. The tests from which these conclusions were reached are described.

Processing Techniques Affect Design of Powder-Metal Parts. P. Schwarzkopf and A. Reis. (Machinist, 1945, vol. 89, Dec. 1, pp. 1184–1187). The design of dies and punches for producing parts with difficult contours by the powder-metallurgy process is discussed and, as examples, the tools used for pressing a coupling ring with six radial slots, a pole piece for a magnet, and a roller-chain sprocket are described.

FOUNDRY PRACTICE

A New Method of Investigating the Behaviour of Charge Material in an Iron Foundry and Some Results Obtained. N. E. Rambush and G. B. Taylor. (Institute of British Foundrymen: Foundry Trade Journal, 1945, vol. 77, Nov. 8, pp. 197–204, 212; Nov. 15, pp. 229–235). *See* Journ. I. and S.I., 1945, No. II., p. 79 A.

Production of Whiteheart Malleable Iron by Annealing in Partially Burnt Town's Gas. I. Jenkins and S. V. Williams. (Institute of British Foundrymen: Foundry Trade Journal, 1945, vol. 77, Oct. 4, pp. 91–99; Oct. 11, pp. 113–116). *See* Journ. I. and S.I., 1945, No. II., p. 80 A.

The Gating and Feeding of Steel Castings. S. T. Jazwinski, E. D. Wells, and S. L. Finch. (Institute of British Foundrymen: Foundry Trade Journal, 1945, vol. 77, Nov. 15, pp. 221–228; Nov. 22, pp. 245–252; Nov. 29, pp. 277–280). *See* Journ. I. and S.I., 1945, No. II., p. 81 A.

Study and Practical Application of a Special Electric-Furnace Nickel-Manganese-Molybdenum Steel for Castings. J. Cournot. (Revue de Métallurgie, Mémoires, 1942, vol. 39, Feb., pp. 61–64). The nickel-chromium-molybdenum steel of a composition corresponding approximately to that of British Standard Steel En 27 (B.S.970, 1942) with a comparatively high nickel content, prescribed by the French specification for making castings 2 m. long of irregular shape, the thickness varying between 8 and 10 mm., weighing about 750 kg., with a tensile strength of at least 70 kg./sq. mm. and 11% elongation, is replaced by a nickel-manganese-molybdenum steel produced in the electric furnace. The electric-furnace melting and refining, the pouring of the casting and the heat-treatment procedure are described in detail.

Steel Castings Replace Forgings. E. B. Bromhead and T. E. Piper. (Iron Age, 1945, vol. 156, Nov. 1, pp. 50–51). The standard of quality and the methods of inspecting steel castings for aircraft which have been set up by Northrop Aircraft Incorporated are outlined.

British Resources of Steel Moulding Sands.—Parts 6 to 10. W. Davies and W. J. Rees. (Journal of the Iron and Steel Institute, 1945, No. II., pp. 71 P–116 P). This is a continuation of the report on the occurrence and properties of the grits and sandstones accessible to steelmaking districts, submitted by the Moulding Materials Sub-Committee of the Steel Castings Research Committee. Parts 1 to 5 were published in Journ. I. and S.I., 1943, No. II., pp. 11 P–111 P. The districts dealt with in the present paper are: Part 6.—The sand deposits associated with the Lincolnshire Wolds. Part 7.—The quarzitic grits and sandstones of Nidderdale and Wharfedale. Part 8.—The quarzitic sandstones in the Cefn-y-Fedw series of North Wales. Part 9.—The rotten-rock moulding sands of Durham and South Northumberland. Part 10.—The

rotten-rock moulding sands of the Midland Valley of Scotland.

Methods of Testing Prepared Foundry Sands. (Institute of British Foundrymen, Nov., 1945, Pamphlet). A Joint Committee consisting of representatives of four interested organizations was formed in 1938 to prepare standard methods of testing foundry sands. The organizations concerned are: The Institute of British Foundrymen, The Iron and Steel Institute, The British Cast Iron Research Association, and the British Non-Ferrous Metals Research Association. The First Report is now issued, and it contains tentative standard methods for the routine testing of all types of prepared moulding and core sand. The methods and apparatus are similar to those advocated by the American Foundrymen's Association; they are intended mainly to emphasise certain essential features which have been found necessary, or at least advisable, in practice, and are not intended to exclude the use of any apparatus which conforms with these essentials.

New Foundry is Model of Mechanization. (Steel, 1945, vol. 117, Nov. 5, pp. 132–134). A description is given of a new American foundry for producing malleable iron castings on a large scale. The melting equipment comprises four cupolas and three furnaces fired with pulverized coal. There are fourteen electric furnaces for malleablizing.

Continuous Production of Steel Castings. G. E. Stedman. (Metals and Alloys, 1945, vol. 22, Sept., pp. 735–741). A description is given of one of the steel foundries of the Columbia Steel Co. where the plant consists of two 30-ton open-hearth furnaces and one 10-ton electric furnace with moulding pits, cranes, heat-treatment and sand-preparation plants, and sidings. Stern frames, anchors and other heavy castings are made.

Cost and Technical Controls in the Foundry. E. W. Harding. (Foundry Trade Journal, 1945, vol. 77, Nov. 29, pp. 275–276). The separate interests of the foundry accountant in reducing costs and of the metallurgist in maintaining the quality of the product are considered, and a means of co-ordinating cost and technical controls is outlined.

PRODUCTION OF STEEL

China's Steel Industry. H. Oresen. (Mechanical Engineering, 1945, vol. 67, Oct., pp. 670–671). The author, who was chief engineer to the Nelson Mission which visited China to report and give advice on the Chinese steel industry, briefly describes the conditions he observed. Several small blast-furnaces producing 25–30 tons of iron per day, 2-ton Bessemer converters and a few 10-ton open-hearth furnaces were observed in the area not occupied by the Japanese. In the province of Szechuan there were several hundred 1-ton charcoal furnaces producing about 1 ton of very pure iron per day; these were operated by farmers during the period that the farms required little attention. The steel plants are unsuitable for expansion, and the cost of producing the steel is high compared with that of imported steel.

The Metallurgical Refining Process by Air Blast. H. Wentrup. (Revue de Métallurgie, Mémoires, 1942, vol. 39, Sept., pp. 280–288; Oct., pp. 313–318; Nov., pp. 345–351; Dec., pp. 370–379). A comprehensive report is presented on the theory and practice of the acid and basic Bessemer processes. This is a French translation of a paper which appeared in Technische Mitteilungen Krupp, Forschungsberichte, 1942, vol. 5, May, pp. 141–186.

Open-Hearth Furnaces in France. P. Bertrand and E. Dupuy. (Revue de Métallurgie, Mémoires, 1942, vol. 39, June, pp. 161–171; July, pp. 193–200). Conditions and methods of operating open-hearth furnaces in France are discussed and compared with open-hearth furnaces in Germany and England. Special attention is paid to the consumption of fuel and refractories in relation to output. The working conditions of gas producers are also examined and a thorough investigation of the following items is recommended: (1) The composition and calorific value of the gas in the gas producer and at the furnace; (2) the composition of the waste gas; (3) the fuel consumption during a heat; (4) the temperature, the pressure and the rate of flow of the gas.

Rational Process of Making Steel Without Inclusions. G. Ranque. (Revue de Métallurgie, Mémoires, 1942, vol. 39, Nov., pp. 331–344; Dec., pp. 360–369; 1943, vol. 40, Jan., pp. 25–29). The author presents a comprehensive report on the formation of non-metallic inclusions in steel and their stability, and describes a practical method for their elimination. In the first part of the article the physical laws which condition the persistence of non-metallic inclusions in the bath of liquid steel are discussed. In the second part a detailed description is given of a procedure applied at the Usines Saint-Jacques for making special and high-quality steels. The method is based on the following main principles: The larger the inclusions, the easier and quicker is their elimination. It is therefore desirable when adding ferro-alloys to create conditions which produce the largest possible inclusions, *i.e.*, to make the additions when the bath is overheated and saturated with dissolved oxides; this procedure also eliminates the risk of introducing hydrogen with the additions. The deoxidation should be done in the last phase of the heat, at a falling temperature, by adding deoxidizing elements to the slag.

Practice Followed in Use of Open-Hearth Charge Ores. C. Denlinger. (American Iron and Steel Institute: Steel, 1945, vol. 117, Nov. 5, pp. 148–150, 188–191). American practice in the use of ores in open-hearth furnaces when scrap was in short supply and high proportions of hot metal were used, is described. The advantages and disadvantages of hard and soft ores and of sinter are pointed out.

Wartime Changes That Will Affect Peacetime Steelmaking. F. G. Norris. (Metal Progress, 1945, vol.

48, Oct., pp. 631–637). Changes in American steelmaking practice introduced under wartime conditions between 1939 and 1945 are briefly reviewed. Two projects of the Bureau of Mines are referred to. One is the production of electrolytic manganese from low-grade domestic ore. The manganese was in the form of small square plates about 0·05 in. thick. Trials at steelworks indicated that electrolytic manganese was certainly as good as ferromanganese but offered no particular advantage. The second is the production of sponge iron using low-grade fuel which in the future will make steelworks less dependent on coking coal.

Operation of an Experimental Open-Hearth Furnace. H. K. Work and W. R. Webb. (Blast Furnace and Steel Plant, 1945, vol. 33, Aug., pp. 959–964; Sept., pp. 1116–1119). *See* Journ. I. and S.I., 1945, No. II., p. 136 A.

The Basic Electric Furnace for Steelmaking. S. D. Gladding and H. C. Bigge. (Metal Progress, 1945, vol. 48, Oct., pp. 642–651). The increase in the production of steel in the basic electric furnace in the United States during the period 1940–1945 is discussed, and the process is described in detail, with special reference to the slag reactions.

Deoxidising a Heat of Acid Electric Steel. C. C. Wissmann. (Metal Progress, 1945, vol. 48, Sept., pp. 499–504, 530). The conditions promoting the removal of oxide impurities from a heat of steel in an acid electric furnace are considered. The equilibrium diagrams for the FeO–SiO_2 and FeO–MnO slag systems are presented. To promote the coalescence of oxide particles and the formation of a fluid slag, the following practice is recommended: Boil until the carbon is down to just below the required analysis, when the slag should be pea-green; deoxidize the metal with silicomanganese with an addition soon afterwards of a little ferromanganese; finally, add ferrosilicon to bring the metal to the required specification.

Acid Electric Process for Steel Castings. J. Juppenlatz. (Metal Progress, 1945, vol. 48, Oct., pp. 638–641). American practice in acid electric-furnace melting in 3–5-ton furnaces is described.

Properties and Care of Ladle Nozzles and Stoppers. L. G. Ekholm and L. D. Hower, jun. (American Institute of Mining and Metallurgical Engineers: Steel, 1945, vol. 117, Oct. 8, pp. 126, 184). The desirable properties in ladle nozzles and stoppers and the manipulation of stoppers to prevent leaking are discussed.

Mechanized Mold Preparation Effects Reduction in Scrap and Scarfing. (Steel, 1945, vol. 117, Oct. 8, pp. 107, 156). A rapid method of preparing ingot moulds is described. Three moulds, measuring $23\frac{1}{2} \times 26\frac{1}{2} \times 80$ in. and heated to 300–500° F., are lifted at once in a special frame and dipped into water to remove dirt; they are then put in position on a platform for spraying. The interior of the moulds is sprayed with powdered pitch by compressed air at 85–95 lb./sq. in. The whole operation takes 2 min.

Mechanized Coating of Ingot Molds. (Iron Age, 1945, vol. 156, Oct. 18, pp. 61–176 B). *See* preceding abstract.

Steel Plant Maintenance. D. S. McLean. (Iron and Steel Engineer, 1945, vol. 22, Sept., pp. 75–78). Recommendations are made on the training of maintenance men, the organization of regular inspection, the stocking of spare parts and the keeping of records of steel-plant maintenance work.

Maintenance. J. A. Shimmin. (Iron and Steel Engineer, 1945, vol. 22, Sept., pp. 79–80). It is shown that efficient maintenance in steelworks can be obtained by: (1) Having a well-organized programme; (2) an adequate and properly trained staff; (3) properly trained process operators; (4) applying standards to maintenance work; and (5) adequate co-operation between engineering, operating and maintenance departments.

Maintenance and Repair of Lifting Magnets. V. E. Holtslander. (Iron and Steel Engineer, 1945, vol. 22, Sept., pp. 65–68). The causes of failure of lifting magnets used in the scrap yard and other departments of the steelworks are examined and the system of inspection, repairs and testing in force at the Inland Steel Company's works is described.

FORGING, STAMPING, AND DRAWING

Influence of Modern Design on Press Forging. (Steel Processing, 1945, vol. 31, Aug., pp. 494–495, 525). Forging and hot-stamping presses which were developed during the war are described, including a 4000-ton forging press and a 200-ton press for small forgings.

Forging Die Design. J. Mueller. (Steel Processing, 1945, vol. 31, Sept., pp. 560–562). The principles to follow in the design of dies for forging rings of regular and irregular section are discussed.

Hot Press Forming of Heavy Steel Plates. (Steel Processing, 1945, vol. 31, Sept., pp. 575–576). Examples of the press-forging of large rings for ventilator fans, brake rims, condenser covers, concrete-mixer drums, and tanks for the chemical industry, of steel up to $3\frac{1}{2}$ in. thick, are described and illustrated.

Precision Forging Press. (Steel, 1945, vol. 117, Oct. 29, pp. 128, 149). A brief description is given of a forging press weighing about 350 tons capable of working at 50 strokes/min.

Drop Forging. J. C. Sharman and R. J. Garland. (Engineering Inspection, 1945, vol. 10, Autumn Issue, pp. 7–17). The development of power-driven hammers for forging is described with notes on the grain flow and directional properties obtained in drop forgings.

Producing 240 mm. Shell at Christy Park Works of National Tube Company. (Industrial Heating, 1945, vol. 12, Sept., pp. 1470–1502). A detailed and well-illustrated description is given of the plant and sequence of processes at the works of the National Tube Co., Pittsburgh, where 240-mm. shells are made.

Induction Heating Develops Widespread Application in the Forging Industry. S. A. Covert. (Steel Processing, 1945, vol. 31, Sept., pp. 577–581). Illustrated descriptions are given of induction-heating installations which have been developed for heating blanks for the mass production of military equipment such as 3½-in. buckles for parachute harness, aluminium propeller hubs, and 75-mm. gun barrels.

The Relationship of the Ability to Cold-Draw Seamless Tubes of Mild Carbon Steel to the Metallurgical Production. E. Siebel, H. Buchholtz, and H. Frank. (Mitteilungen aus dem Kaiser-Wilhelm-Institut für Eisenforschung, 1942, vol. 24, No. 8, pp. 105–122). Investigations were undertaken to find a method of calculating the maximum reduction which can be achieved in one draw when cold-drawing seamless tubes of low-carbon steel. The maximum possible reduction is a function of the product of three factors, which are: (1) The maximum possible increase in strength (*i.e.*, the strength after drawing divided by the mean of the strengths before and after drawing); (2) the maximum possible deformation efficiency; and (3) the maximum possible strengthening efficiency (*i.e.*, the drawing force divided by the product of the section area and strength after drawing). The theoretical value obtained from these factors was about 65%, but in actual drawing tests the value did not exceed 56·6%. The value of factor (1) was about 1·4, which was obtained for open-hearth rimming steel annealed before cold-drawing. The best value obtained for factor (2) was about 75%. A maximum value of 97·4% was obtained for factor (3) for thin-walled tubes; for killed steels the average value was about 90% and for rimming steels about 80%. In general, it can be said that a 50% reduction in area can be achieved in one draw when making thin tubes of soft killed steel when certain conditions are complied with, and such tubes have good deformation properties and do not age-harden.

Precision Bolts and Studs. (British Engineering Export Journal, 1945, vol. 28, Nov.-Dec., pp. 319–324). The sequence of processes in the manufacture of precision bolts and studs of a medium-carbon manganese-molybdenum steel developed by a Glasgow company is described.

Making Bolts and Studs. (Electrical Review, 1945, vol. 137, Nov. 30, pp. 769–773). Details are given of the motors and other electrical equipment used to drive the drawing and heading machines at the works referred to in the preceding abstract.

Lubrication in the Drawing of Metals. S. Spring. (Steel, 1945, vol. 117, Oct. 8, pp. 120–125, 180–182; Oct. 15, pp. 124–134, 180). Methods of testing the physical properties of drawing lubricants are described.

The Progress of Fine Wire Drawing. S. C. Avallone. (Wire and Wire Products, 1945, vol. 20, Sept., pp. 623–624, 649). Some of the methods adopted in the United States to increase the production of fine wire are briefly reviewed. It was found advantageous to use metallic soaps such as calcium or aluminium stearate as lubricants.

Drafting Calculations for the Wire Mill. T. C. Woolfenden. (Wire Industry, 1945, vol. 12, Oct., pp. 531, 534). Methods of calculating the number of dies and the die sizes to effect a given reduction of gauge in wire-drawing are explained.

HEAT-TREATMENT

Heat Treating Diagrams—S or TTT-Curves. F. R. Morral. (Metal Progress, 1945, vol. 48, Oct., pp. 818–831). The author prefers the designation "TTT-curve" (time-temperature-transformation) as the curves for many steels are not of the S shape. The use of the curves is explained and an indexed list of all published TTT-curves with analyses of the steels and references to the literature is presented. A procedure for drawing the curve for a steel not in the list is described.

Contribution to a Study of the Deep Case-Hardening of Special Steels. G. Delbart. (Revue de Métallurgie, Mémoires, 1942, vol. 39, Oct., pp. 295–312). The results of mechanical tests on certain low-alloy case-hardened steels containing chromium, chromium-molybdenum, nickel-chromium and nickel-chromium-molybdenum are presented. Each of the steels was submitted to the same process of case-hardening, and the depth of the cases was examined. It was found that the hardened layer was deeper for the above steels than for plain carbon steel, the chromium-molybdenum steel having the deepest case. The depth of the layer varied between 3·1 and 3·9 mm. after 40 hr. case-hardening and water-quenching from 960° C., and between 4·6 and 5·7 mm. when the process lasted 102 hr.; oil-quenching resulted in 1·6–3·5 mm. and 2·0–5·4 mm. depth of case after 40 and 102 hr., respectively. The results of tensile and bend tests combined with the microscopical examination showed that martensite on the surface and ferrite + cementite in the core was a structure to be avoided.

Cyanide Nitriding Increases Hardness of High-Speed Cutting Tools. J. E. Lynch and C. W. Snyder. (Machinist, 1945, vol. 89, Dec. 1, pp. 1190–1192). A nitriding treatment which increases the hardness of hardened high-speed steel tools is described. The treatment is in five stages: (1) Preheating slowly to 800° F.; (2) immersing in a molten cyanide bath at 900–1100° F. for 15–60 min. and cooling in air to 150° F.; (3) washing in water and soda at 150° F., rinsing, and drying; (4) tempering for 1 hr. at 1000° F. in a nitrate salt bath; and (5) cooling in air to room temperature, washing in water and soda at 150° F., rinsing, and drying.

Some Applications of Sub-Zero Treatment to Steel. (Machinery, 1945, vol. 67, Nov. 22, pp. 580–581). Some examples are given of the beneficial effects obtained by the cold-treatment at − 120° F. for a few hours of high-speed steel tools.

Electrode Salt Baths. (Machine Shop Magazine, 1945, vol. 6, Oct., pp. 88–92). A detailed description is given of an electrode salt-bath furnace which is a

self-contained unit. It is designed to cover the temperature range of 550–1380° C. The times taken to reach 600°, 900° and 1350° C. are 45, 50 and 60 min. respectively. Once these temperatures have been reached, the approximate powers required to maintain them are 1, 2 and 4 kWh. respectively.

Salt Baths—In Wartime—In Peacetime. W. W. Winters. (Metal Progress, 1945, vol. 48, Oct., pp. 815–817). Some modern heat-treatment plants using molten salt baths are described. The advantages of refractory pots, which can be made up to 20 ft. long, are pointed out.

Conveyorized Non-Decarburizing Heat Treatment of Gears. W. J. Bornholt and H. E. Scarbrough. (Iron Age, 1945, vol. 156, Oct. 18, pp. 54–57). An illustrated description is given of a continuous heat-treatment plant for hardening and tempering gears.

Gas Carburizing. E. S. Kopecki. (Iron Age, 1945, vol. 156, Oct. 18, pp. 50–53; Oct. 25, pp. 52–58; Nov. 1, pp. 60–63). The theory and practice of gas carburizing are discussed. In Part I. the selection of steel for carburizing and the effect of the grain size are dealt with. In Part II. the gas reactions and the control of soot deposits are considered. In the concluding part bright-carburizing, and pit and retort furnaces are described. A bibliography with 59 references is appended.

The Use of Protective Atmospheres in Heat-Treatment Furnaces. M. Fourment. (Revue de Métallurgie, Mémoires, 1942, vol. 39, Apr., pp. 97–103). After discussing briefly the importance which the use of protective atmospheres during heat-treatment has for steel and non-ferrous metals, the author analyses the properties of various protective gases and gives an illustrated description of installations of heat-treatment furnaces.

Attempts to Accelerate the Nitriding of Steel. E. Kunze. (Archiv für das Eisenhüttenwesen, 1944, vol. 18, Sept.-Oct., pp. 57–60). The literature on methods of accelerating the process of nitriding steel is critically reviewed. The functions in the nitriding process of atomic nitrogen, the number and type of active spots per unit area of surface, the solubility of nitrogen in nitrided steel, and the diffusion process are discussed. The application of certain granular materials, calcium chloride in particular, increases the rate of absorption of nitrogen but does not increase the concentration at the surface. Phosphatizing before nitriding is the only method of increasing both the depth and the concentration at the surface.

Accelerating the Nitriding of Steel by Glow Discharge. H. Bennek and O. Rüdiger. (Archiv für das Eisenhüttenwesen, 1944, vol. 18, Sept.-Oct., pp. 61–67). If a glow discharge is created in an atmosphere containing nitrogen, nitrogen ions with a positive charge will be attracted to the cathode at high velocity. This principle has been applied to the nitriding of steel. An apparatus is described in which specimens (30 mm. in dia. and 8 mm. thick) of chromium steel and chromium-molybdenum steel were made the cathode in a quartz cylinder held within a discharge tube. Current was supplied from a 110-V./5000-V. transformer and ammonia was used as the source of nitrogen. The discharge tube was exhausted by a two-stage diffusion pump with an oil backing pump. Several tests were run under various conditions of time, temperature, suction and current. The depth of the nitrided layer and the Vickers hardness were determined and compared with the results obtained by the normal nitriding process. For equal times of treatment up to 7 or 8 hr. greater hardness and a slightly deeper case were obtained by the glow-discharge method. With increasing time the effects of the treatments became more and more similar. The best results were obtained when the current was sufficiently strong for the specimen to be heated by the bombardment. Prominent corners and edges were uniformly nitrided by the glow-discharge process.

Annealing High Carbon Wire Stock. J. H. Loux. (Wire and Wire Products, 1945, vol. 20, Oct., pp. 742–749). Special atmospheres for annealing high-carbon steel wire are discussed with particular reference to a double-cracked gas made from natural gas.

The Annealing of High-Quality Electric Welds in the Construction of Boilers and Vessels. H. Busch. (Archiv für das Eisenhüttenwesen, 1942, vol. 16, Nov., pp. 187–195). The effects of stress-free annealing and of normalizing treatments on electrically welded steel boilers and vessels are compared, and a modern annealing furnace for large vessels is described. Tests were made on specimens from a shell plate, bent cold and electrically welded, in which the outer fibres were elongated by 4%. There was a very slight reduction in the impact strength of specimens from a position 4–5 mm. from the weld. For satisfactory stress-free annealing the original boiler plate must be properly normalized. Stress-free annealing was found to be a better treatment than normalizing for vessels to be used at − 50° C.

High-Frequency Induction Heating—A Comment. E. Gregory. (Machinery, 1945, vol. 67, Nov. 29, pp. 608–610). An example of the successful induction-hardening of a layshaft with four gears is described. The heating times for the four gears were 15, 18, 20 and 30 sec. respectively. Very accurate measurements were taken before and after hardening. In no instance was a difference of 0·0006 in. exceeded. The maximum spacing error from tooth to adjacent tooth was increased by 0·0003 in. Data on the cost of the process are discussed and it is shown to compare favourably with that of cyanide hardening.

Induction Heating and Heat Treating (A General Statement). H. B. Osborn, jun. (Metal Progress, 1945, vol. 48, Oct., pp. 801–806). General considerations governing the power and frequency requirements for induction heat-treatment are discussed with notes on the relations between frequency, diameter of bar and penetration of the heating effect. The hardening of the internal surfaces of cylinder liners, gun barrels and wheel hubs is dealt with briefly.

Important Achievements of Induction Heating—Frequencies up to 10,000 Cycles. H. B. Osborn, jun. (Metal Progress, 1945, vol. 48, Oct., pp. 806–810). The relative merits of the motor-generator set and the vacuum-tube oscillator for producing current at frequencies up to 10,000 cycles/sec. are pointed out

and some outstanding examples of hardening carried out at this frequency are described.

Important Achievements of Induction Heating—Frequencies from 100,000 to 500,000. J. J. Fox. (Metal Progress, 1945, vol. 48, Oct., pp. 806–807, 810–812). The methods of producing high-frequency currents in the 100,000–500,000 cycle/sec. range are described and some of its useful characteristics when hardening steel are pointed out.

Important Achievements of Induction Heating—Vacuum Tube Units. J. W. Cable. (Metal Progress, 1945, vol. 48, Oct., pp. 806–807, 813–814, 832). The advantages of using high frequencies in the 100,000–500,000 cycle/sec. range for induction hardening are discussed. One is the ability to concentrate heat in shallow surface layers. At 10,000 cycles the theoretical penetration is 0·020 in. in steel, whereas at 375,000 cycles it is reduced to 0·004 in. A second is the ability to heat small diameters and thin sections, and a third advantage is that the energy can be transferred over greater distances from the coil to the metal.

Radio Frequency Heating. (Metallurgia, 1945, vol. 32, Oct., pp. 255–256). Some notes on a recent exhibition of high-frequency heating apparatus are presented. Particulars of its application for the heat-treatment of steel are given.

WELDING AND CUTTING

Five Years of Progress in Welding. W. Spraragen. (Metal Progress, 1945, vol. 48, Oct., pp. 905–916). Progress in the welding of ferrous and non-ferrous metals during the period 1940 to 1945 is reviewed.

Hot-Shearing Blades. A. T. Cape. (Steel, 1945, vol. 117, Nov. 5, pp. 140, 178–180). The technique for welding nickel-chromium-molybdenum steel on the prepared edges of shear blades is described. The body of the blade is made of 0·4–0·5%-carbon steel. The welded edges are ground to form the cutting edges of the blade.

Hidden-Arc Welding of 13-Gage Steel. H. E. Cable. (Iron Age, 1945, vol. 156, Nov. 1, pp. 52–53). A description is given of a method of automatic welding which was developed for joining the seams of bomb boxes made of 13-gauge steel sheet. The edges of the sheet were held in a jig which also formed a V groove into which the powdered flux was fed at the side of a guide wheel. The electrode wire was fed from a coil into the flux. The welding speed was about 120 in./min.

Produces Over 19,000 Miles of Electric Welded Tubing. (Steel, 1945, vol. 117, Oct. 15, pp. 114–115, 144–146). A description is given of two new tube mills operated by the Babcock and Wilcox Tube Co. The hot-rolled coils of skelp are accurately sized, cleaned and pickled and then passed through forming rolls to continuous resistance-welding machines. The two mills have a capacity of 4000 tons/month of tubes from $\frac{3}{4}$ to 4 in. in dia.

Quality Control during Production of Electric Resistance Welded Tubing. S. O. Evans. (Welding Journal, 1945, vol. 24, Sept., pp. 805–810). A description is given of the testing technique for resistance-welded steel tubing set up by the Babcock and Wilcox Tube Co. It consists of the Magnaflux test supplemented by a flattening test, the latter test being designed to reveal flaws on the inside of the tube which are not detectable by the Magnaflux test.

Processing and Fabrication of Stainless Steel. (Steel Processing, 1945, vol. 31, Sept., pp. 567–573). Recommendations are made on the shearing, forming, welding, machining, grinding and polishing of stainless steel.

Weldability Tests of Valve Body Material. L. H. Carr. (Welding Journal, 1945, vol. 24, Sept., pp. 446-S–451-S). A procedure for testing the weldability of the steel used for cast steel valve bodies is described. The procedure is based on determinations of the heat input under various conditions of welding and on the results of Jominy end-quench tests.

The Effect of Hammer Blows on Welds Containing Cracks and/or Inclusions. E. A. Ratzel. (Welding Journal, 1945, vol. 24, Sept., pp. 455-S–458-S). The results of a test designed to determine qualitatively the effect of hammer blows on a welded specimen having a known initial defect (deliberately made) indicate that the value of the hammer test to find defects in welded pressure vessels is questionable.

Alloy Welding Wire from Powder Metallurgy. F. G. Daveler and P. H. Aspen. (Welding Journal, 1945, vol. 24, Sept., pp. 842–844). A description is given of the development of a method of making electrodes for welding alloy steels. It consists of building up a mixture of powdered materials by the powder-metallurgy process round a wire core. For instance, an electrode for welding stainless steel is made by holding a core wire $\frac{5}{32}$ in. in dia. of 0·03%-carbon steel in the centre of a die $\frac{1}{4}$ in. in dia. and filling up the annular space with a mixture of powdered ferrochromium, ferrosilicon, ferromanganese and pure nickel adjusted to produce the required analysis. The mixture is compressed and sintered in the die and a flux coating is added.

Machine Gas Cutting. R. M. Dennis. (Welding Journal, 1945, vol. 24, Sept., pp. 839–842). An illustrated description is given of some of the equipment and machines at the Lukens Steel Company's works which were designed for the multiple oxy-acetylene cutting of shapes out of steel plate of various thicknesses.

MACHINING

The Cutting Tools of World War II. M. F. Judkins. (Metal Progress, 1945, vol. 48, Oct., pp. 901–904). The development of cutting tools, in particular the tungsten-carbide-tipped tools, in the United States in the war period 1939–1945 is briefly described and recommendations on the method of welding or brazing the tip to the shank are made.

How to Conserve Tool Steel and Obtain Longer Tool Life. R. C. Gibbons. (Steel, 1945, vol. 117, Oct. 22, pp. 112–113, 150–157). Methods of effecting economies in the use of tool steel for machining are discussed under the following headings: (1) Control of the material being cut; (2) selection of tool steels; (3) use of composite or tipped tools; (4) redesign of tools; (5) surface preparation; (6) use of the tool; (7) cutting fluids; and (8) salvage.

The Mechanism of Tool Vibration in the Cutting of Steel. R. N. Arnold. (Engineer, 1945, vol. 180, Nov. 2, pp. 355–356; Nov. 9, pp. 379–380). An investigation of the factors affecting tool vibration on a 10-in. centre lathe is reported. A theory is developed to explain the profiles obtained on the work and an explanation is offered of the origin of the vibration and the mechanism by which it is sustained.

Milling Cast Iron with Carbides. M. Field and W. E. Bullock. (Mechanical Engineering, 1945, vol. 67, Oct., pp. 647–658). The results of milling-cutter tests on cast iron with a carbide-tipped cutting tool are reported and discussed. The machinability of cast irons can only be compared by studying the characteristic curves relating tool life to cutting speed and feed per tooth. There is a maximum tool-life point towards the lower end of the speed range. Relatively large differences in machinability exist with ferrous castings of approximately equal Brinell hardness. A cutter combining a fairly large negative radial rake with a large positive axial rake and a large corner angle will remove a considerably greater volume of metal before becoming blunt than the conventional positive-rake cutters.

Carbide Milling of Steel. A. W. Meyer and F. R. Archibald. (Mechanical Engineering, 1945, vol. 67, Oct., pp. 659–667). Tests to establish the optimum conditions, especially the best tool contour, for milling different steels at high speed with carbide-tipped tools are described. Four sets of conditions applicable respectively to steels containing 0·10%, 0·20% and 0·40% of carbon and to a heat-treated 1·75%-nickel and 1%-chromium steel were established.

CLEANING AND PICKLING OF METALS

Blast Cleaning of Metal. A. L. Gardner. (Metal Progress, 1945, vol. 48, Oct., pp. 959–961). The theory and practice of shot-blast cleaning are discussed. It is a mechanical process and can be used regardless of the surface shape or indentations. By choosing the size of the abrasive grains, their velocity, and the angle of impact, almost any type of surface finish can be obtained. With steel shot about $\frac{1}{32}$ in. in dia. and compressed air at 80 lb./sq. in. a velocity of about 250 ft./sec. was obtained and found to be satisfactory.

What Is a "Clean" Surface? E. H. Lyons, jun. (Electrochemical Society, Oct., 1945, Preprint No. 88–1). Only rarely, if ever, does a metal particle to be plated enter the bath with a truly clean surface, even after the most careful cleaning procedure. The effects of various types of films on surfaces to be plated are classified according to the effects they produce on the electroplate. The surface required for electrodeposition is one which will receive a smooth adherent metal deposit, but this is not necessarily an absolutely clean surface. In general, an acceptable surface is one on which "objectionable surface films have been replaced by films more suitable and acceptable for electroplating."

Surface Preparation of Cast Iron. J. H. Shoemaker. (Metal Progress, 1945, vol. 48, Oct., pp. 961–962). The Kolene process of cleaning cast iron in preparation for enamelling is described. It consist of putting the casting in a bath of molten salt at 500° F. and passing a current at 6 V. with the work as the cathode so as to cause reactions which reduce scale or rust at the surface. The polarity is then reversed so as to oxidize impurities such as sulphur, phosphorus and graphite in the bare metal surface. Finally, the current is again reversed so as to remove the iron oxide formed during the previous cycle and a surface of almost pure ferrite is left.

Metals, Finishes and Finishing Processes. E. Engel. (Iron Age, 1945, vol. 156, Sept. 6, pp. 70–79; Sept. 13, pp. 64–71; Sept. 20, pp. 74–83; Sept. 27, pp. 65–68). Numerous tables are presented giving data on the corrosion resistance and the coefficients of friction of plated surfaces and information for comparing degreasing, descaling and electrolytic polishing procedures.

Metal Pickling. A. J. T. Eyles. (Mechanical World, 1945, vol. 118, Oct. 26, pp. 476–478). Modern pickling practice is described with special reference to the use of acid-resisting plastic equipment.

The Surface Preparation of Certain Cold-Worked Steels by Pickling. P. D. Liddiard. (Sheet Metal Industries, 1945, vol. 22, Sept., pp. 1731–1736). A solution containing nitric and sulphuric acids is recommended as a satisfactory bath for pickling steel which has been cold-reduced without removal of the lubricants before heat-treatment. Such "difficult" steels can be given a satisfactory surface in this way before coating with other metals or paints.

Continuous Pickler for Coiled Material. A. S. Hellstrom. (Iron and Steel Engineer, 1945, vol. 22, Aug., pp. 59–61). An illustrated description is given

of a continuous pickling plant developed by the Greer Steel Company, Indiana. The plant is designed to save floor space, and is only 150 feet long. The end of a coil of strip is threaded through scale-breaking rollers and the coil is wound up on a reel block 18 in. in dia. The block is reversed and the coil is back-spun to a predetermined outside diameter thus creating an air space between the layers. A mandrel is passed through the coil; there are sprockets on each end of the mandrel and these engage in chains passing along each side of the pickling tank. About two-thirds of the coil is submerged in the acid, but, as the coil rotates as it travels along the tank, all parts of it come in contact with the acid.

Pickling with Submerged Combustion. H. N. Snowden. (Wire and Wire Products, 1945, vol. 20, Oct., pp. 750–751). The development of "submerged combustion" heating equipment for pickling tanks for wire is described. This equipment consists of special burners and igniting devices which enable gas flames to be burnt under the surface of the pickling solution.

The Rôle of the Inhibitor in the Fixation of Hydrogen in the Acid Pickling of Polycrystalline Iron. L. Moreau. (Comptes Rendus, 1944, vol. 218, pp. 353–355). Fatigue tests on specimens of polycrystalline and monocrystalline iron pickled in acid with and without an addition of an inhibitor (2% of pyridine) were carried out. There was only a very slight increase in the number of bends to fracture in the two cases (*a*) polycrystalline iron using the inhibitor, and (*b*) monocrystalline iron without the inhibitor. The inhibitor prevents the acid from attacking the intergranular material.

COATING OF METALS

Adhesion of Electrodeposits. B. F. Lewis. (Monthly Review of the American Electroplaters' Society, 1945, vol. 32, Feb., pp. 139–147). Methods of improving the adherence of electrolytic coatings on steel and other metals are discussed. The recommendations made include the following: (1) The surface to be plated must be absolutely clean; (2) the cleaning process should not leave a cold-worked layer on the surface; (3) buffing is better than polishing; and (4) the electrodeposition, once started, must not be interrupted until the desired thickness is obtained.

The Reclaiming and Hardening of Engineering Components by Electro-Deposition. H. Merryweather. (Transactions of the Manchester Association of Engineers, 1944–45, pp. 153–176). *See* Journ. I. and S.I., 1945, No. II., p. 63 A.

Protection of Metals for Industrial Process Piping. L. D. Van De Bogart. (Electrochemical Society: Steel, 1945, vol. 117, Oct. 15, p. 117). The advantages of nickel-plating the interior of steel tubes and of phenolic resin coats on cast-iron pipes are discussed.

Automotive Plating Survey. R. C. Olsen. (Electrochemical Society: Steel, 1945, vol. 117, Oct. 15, pp. 118–119). A list is presented showing the relative deterioration of various automobile parts after two years' wear.

Chromium Plating. J. Poor. (Electrochemical Society: Steel, 1945, vol. 117, Oct. 15, p. 119). The advantages of porous chromium plating on the walls of the cylinders of internal combustion engines are discussed.

The Outlook for Electrolytic Tin Plate. K. W. Brighton. (Iron and Steel Engineer, 1945, vol. 22, Aug., pp. 37–39). Particulars are given of the weights of the electrolytic tin coatings on steel specified by the United States War Production Board for cans for various fruits and vegetables. The results of some corrosion tests of cans containing prunes are given.

Some Factors in the Production of Electrolytic Tin Plate. T. G. Timby. (Iron and Steel Engineer, 1945, vol. 22, Aug., pp. 40–43). The precautions to be taken in the production of bright tinplate by the electrolytic process are discussed and curves are presented showing the variations in current density at different positions in a potassium stannate bath using flat and corrugated anodes.

Tin Fusion by Radiant Tube Heating. H. L. Halstead. (Iron and Steel Engineer, 1945, vol. 22, Aug., pp. 49–50). A brief description is given of six radiant-tube furnaces at the works of the Bethlehem Steel Co. which are used for reflowing the tin on electrolytically coated steel strip. These are tower furnaces 36 ft. high, divided vertically into two chambers. The strip, which is 28 in. wide, passes up through the preheating chamber, over a roller at the top and down through 34 radiant-tube elements fired with coke-oven gas and air. The strip is preheated to 150° F. and leaves the bottom of the furnace at 450° F. at a speed of 275 ft./min. This was found to be a very economical method of heating the strip.

Fusion Brightening of Electro-Tinplate. (Iron Age, 1945, vol. 156, Oct. 18, p. 57). A technique has been developed at the Illinois Institute of Technology for taking motion pictures of the fusion of tin on electrolytic tinplate. Four pictures at 60 diameters are reproduced showing different stages of the process.

Chromium, Silicon and Aluminium Impregnation of Steel. A. M. Borzdika. (Stal: Iron Age, 1945, vol. 156, Oct. 18, pp. 58–61). An English translation of a paper from the Russian journal "Stal" is presented. Experiments in impregnating steel with chromium, silicon and aluminium, using solid and gaseous media, are described. Media in powder form are not recommended. Gaseous cementation using the chlorine compounds of the respective metals as catalysts is advocated for industrial purposes.

Improvements in Other Protective Metallic Plates. R. B. Saltonstall. (Metal Progress, 1945, vol. 48, Oct., pp. 965–967). Electrolytic coatings other than nickel and zinc are discussed. In particular a method of preparing a bearing for aeroplane engines is de-

scribed. It consists of plating about 0·050 in. of silver on the steel, machining this to 0·001–0·0015 in. undersize, building up to size by lead plating and finishing with a flash coating of indium which is later diffused into the lead by heating.

Rubber Lined and Rubber Covered Equipment. H. C. Klein. (Electrochemical Society: Steel, 1945, vol. 117, Oct. 15, pp. 120, 172, 174). The advantages of synthetic-resin coatings on tanks, pipes and drums to resist the attack of oils and acids are discussed.

The Formation of Metal-Sprayed Deposits. W. E. Ballard. (Proceedings of the Physical Society, 1945, vol. 57, Mar. 1, pp. 67–83). The difficulties of research on the metal-spraying process are examined. Some of these have been overcome by the use of the high-speed cinema camera, which has suggested that the spray metal pulsates rapidly and that a retraction of the deposited agglomerates of particles takes place on the surface. A theory is put forward to show that surface tension plays a considerable rôle both in the pulsation of the spray and in the ultimate structure of the coating. Indications are given that the amount of metal sprayed in unit time is controlled by well-known physical laws, and an empirical formula for speed of working is given and examined. Developing the theory of the action of surface tension at the moment of impact, explanations are given for certain phenomena observed when depositing metal on smooth glass and roughened metallic surfaces, including the problem of adhesion. Some effects of the spread of the spray, marginal deposits, and the temperature of deposition are noted, and a tentative explanation for the variation in the percentage lost when spraying different metals is advanced.

Modern Installations for Spraying Parts. E. J. Cartwright. (Machinist, 1945, vol. 89, Nov. 10, pp. 1069–1070). Equipment for spraying metal parts with paint, enamel or lacquer is described with special reference to apparatus for removing oil and moisture from the compressed air.

Porcelain Enamels. G. H. McIntyre. (Electrochemical Society: Steel, 1945, vol. 117, Oct. 15, pp. 119–120). The preparation of porcelain enamel coatings is described and some of their corrosion-resistant properties are discussed.

Methods of Assessment of Anti-Fouling Compositions. K. A. Pyefinch. (Journal of the Iron and Steel Institute, 1945, No. II., pp. 229P–243P). The colonization of a toxic surface immersed in the sea is dependent upon a number of factors, of which the most important may be termed the seasonal and the sensitivity factors. The former, imposed by the limited length of the breeding season of many marine organisms, expresses the availability of settling stages, spores or larvæ, for settlement; the latter, produced by the varying sensitivities of these settling stages to the poisons released from the paint, governs the ability of the spores or larvæ to settle and develop. Other factors play their part, but the sensitivity and seasonal factors are much the most important and any scheme of assessment which attempts critically to assess the performance of an anti-fouling composition, should be based on these two factors.

The present paper gives an account of a method of assessment which attempts to allow for these factors. The wide range of sensitivity of the animals and plants commonly settling on exposed panels has enabled a fouling sequence to be constructed and this is used, with due allowance for seasonal effects, as a means of placing anti-fouling compositions under test in one of five categories, which represent five stages of increasing inadequacy of protection against fouling. This method has given satisfactory results with a large number of exposures of experimental anti-fouling compositions but, since it is an evaluation of a series of biological inter-relationships, it cannot always be rigidly applied. To some extent, each case must be treated on its merits, and examples are given of detailed assessments which illustrate difficulties or points of particular interest in the application of the method.

Post-War Corrosion Inhibiting Primers. W. G. Huckle and H. S. Davidson. (Paint Industry Magazine, 1945, June, Reprint). Extensive tests on steel panels exposed to the action of the tide at Florida so as to compare the corrosion-resisting properties of various paint formulations are reported, the principal object being to compare zinc-yellow-pigmented priming coats with other primers and to determine the most suitable vehicle. Zinc-yellow primers were found to be superior to and less expensive than red-lead primers.

A New Coating Thickness Gage. S. Lipson. (A.S.T.M. Bulletin, 1945, Aug., pp. 20–23). A new thickness gauge is described in which electromagnetic principles are applied to determine the thickness of non-magnetic coatings on steel.

PROPERTIES AND TESTS

The Behaviour under Tensile Stress of Metals Deformed by Compression.—Parts I. and II. F. Körber, A. Eichinger and H. Möller. (Iron and Steel Institute, 1946, Translation Series, Nos. 258 and 259). These are English translations of the two parts of a paper which appeared in Mitteilungen aus dem Kaiser-Wilhelm-Institut für Eisenforschung, 1941, vol. 23, No. 9, pp. 123–133, and 1943, vol. 26, No. 6, pp. 71–89 respectively; they have been abstracted previously (*see* Journ. I. and S.I., 1942, No. I., p. 197 A and 1944, No. II., p. 161 A).

A Discussion on the Notch Impact Test and Its Interpretations. A. Fisher. (Metallurgia, 1945, vol. 32, Sept., pp. 192–198; Oct., pp. 281–284). The obstacles which have prevented much progress towards rationalizing design methods for notched components are discussed and suggestions on impact-testing methods and the interpretation of the results

are made. A new formula is given which is claimed to provide a rational interpretation and expression of "notch sensitivity."

Some Problems of the Metallic State. Sir Lawrence Bragg. (North-East Coast Institution of Engineers and Shipbuilders: Engineering, 1945, vol. 160, Nov. 23, pp. 433–435). An outline is given, from the viewpoint of the physicist, of what gives to metals their characteristic properties and of the factors which determine their mechanical strength. In the initial annealed state there are large regions of highly perfect crystalline structure in the metal. When slip occurs, it runs for long distances, the parameter t (the average distance between faults, where unconformable mosaic elements meet) being large, and the yield point low, but this very act of yielding creates dislocations which form new interfaces where differently orientated mosaic fragments meet. The parameter t diminishes and the crystal becomes stronger. At the same time the interfaces are centres of highly localized strain in which the energy of cold-work resides. As deformation proceeds, the mosaic elements yield one after another along a plane of slip where the atoms move on one each time. The largest elements are the weakest and yield first. The process cannot be carried on beyond a certain limit because of the recrystallizing power of the metal. However much cold-work is put into the metal, a limiting amount only can be retained. This corresponds to the crystal structure being broken into fragments of limiting small size, fitting as unconformably to each other as is possible geometrically. When this limit is reached, the elastic limit of the metal is determined approximately by $ns \div t$, where n is the rigidity modulus, and s the distance between neighbouring atoms.

The Structure of Cast Steels. Brittleness and Intergranular Fracture. H. Jolivet. (Revue de Métallurgie, Mémoires, 1942, vol. 39, Aug., pp. 233–246; Sept., pp. 257–264). Certain special steels show brittleness which is not removed by heat-treatment but is characterised by intergranular fracture. The hot working of steel tends to improve its properties in this respect in both longitudinal and transverse directions. The investigation of steel the solidification of which occurs in the δ-phase has shown that the brittleness is due to a lack of cohesion between the austenite grains, or to the secondary structure, which, in this case, has no direct connection with the dendritic segregation. The brittleness originates from the precipitation either of cementite or of non-metallic inclusions in the austenite grain boundaries.

The Determination of Damage Curves for Steel. F. Bollenrath and H. Cornelius. (Archiv für das Eisenhüttenwesen, 1942, vol. 16, Aug., pp. 49–56). Wöhler curves and damage curves for smooth and notched specimens of a chromium-molybdenum steel were constructed from data obtained from five different laboratories and the relationship of the fatigue to the tensile properties was studied.

The Fatigue Strength and the Static Elastic Limit. A. Schaal. (Archiv für das Eisenhüttenwesen, 1942, vol. 16, July, pp. 21–24). The X-ray technique was employed to measure the actual stress condition in the surface of specimens which had been subjected to tension-compression and to torsional fatigue tests. The determinations were made with the load increasing by stages until fracture occurred. At the stage just before cracks appeared, the residual stress, as determined by X-rays, plus the applied fatigue stress was found to be approximately equal to the elastic limit in the static tensile test. The ratio of the fatigue strength to the elastic limit for steel and light alloys decreased steadily with increasing elastic limit.

A Fatigue Testing Machine for Caquot Test Pieces. R. Guillery. (Revue de Métallurgie, Mémoires, 1942, vol. 39, Jan., pp. 27–29). A description is given of a fatigue-testing machine, designed by the author, to test specimens standardized by the Services de L'Aeronautique. By submitting the specimen to alternating bend tests at 6,200 cycles/min., the time of testing is reduced by half.

Two New Microhardness Testers. E. B. Bergsman. (Industrial Diamond Review, 1945, vol. 5, Nov., pp. 258–262). This is a translation of part of the author's paper in Jernkontorets Annaler, 1944, vol. 128, No. 3, pp. 81–104 (*see* Journ. I. and S.I., 1944, No. II., p. 112 A). It gives detailed descriptions of two new microhardness testing instruments.

"H" Steels and Their Specification. L. E. Ekholm. (Metal Progress, 1945, vol. 48, Oct., pp. 673–683). The work of the Technical Committee on Alloy Steel of the American Iron and Steel Institute in conjunction with the S.A.E. General Standards Committee in drawing up hardenability specifications is described. The compositions of a number of hardenable steels with their maximum and minimum hardenability curves are given. These curves are obtained by plotting the Rockwell hardness values obtained at increasing distances from the quenched end in the Jominy test. The utility of this method of specifying steels has been found satisfactory by both the steelmaker and the user.

The Supersonic Reflectoscope for Interior Inspection. F. A. Firestone. (Metal Progress, 1945, vol. 45, Sept., pp. 505–512). A description is given of the principles and application of the supersonic reflectoscope for the non-destructive testing of metals for flaws. This instrument was developed at the University of Michigan. A quartz crystal in contact through an oil film with the bar to be tested emits a few sound waves of very short wave length. This group of waves is reflected from the face of the bar farthest away from the crystal. When the reflected waves strike the crystal an e.m.f. is generated in it and the time of arrival is indicated on the screen of a cathode-ray oscilloscope. Any flaw causes part of the wave group to be reflected, and this "echo" arrives at the crystal before the echo from the opposite face of the bar. A measurement of the time lag between the arrival of the two echoes indicates the distance of the flaw from the end of the bar.

The Supersonic Flaw Detector. E. N. Simons. (Metal Progress, 1945, vol. 45, Sept., pp. 513–516). An apparatus of British design for detecting flaws in bars and billets, based on the reflection of supersonic waves is described. Whereas in the American apparatus referred to in the preceding abstract the same

quartz crystal is used for emitting the waves and receiving the echoes, in the British instrument separate crystals are used for emitting and receiving. The latter instrument is capable of detecting flaws within a region of from ½ in. to 12 ft. from the surface.

Statistical Quality Control of Methods and Materials. E. G. Olds. (Engineering Materials and Processing Methods, 1945, vol. 22, Oct., pp. 1097–1101).

Magnetic Sorting of Steels. F. P. Cobb. (Engineering Inspection, 1945, vol. 10, Autumn Issue, pp. 18–22). A magnetic method of testing and classifying steel bars is described; it is based on the shape of the hysteresis curve of the material which is shown on the screen of a cathode-ray tube.

Instruments to Establish Identity—Magnetic Comparators. J. J. Smith. (Metal Progress, 1945, vol. 48, Oct., pp. 997–1000). Brief descriptions are given of instruments for comparing the magnetic properties of bars with each other or with those of a standard specimen.

Instruments to Establish Identity—High Frequency Devices. P. E. Cavanagh. (Metal Progress, 1945, vol. 48, Oct., pp. 1000–1003). A description is given of the "Cyclograph" apparatus for testing the magnetic properties of steel bars. Using a 60-cycle, 110-V. A.C. source, this apparatus can be adjusted to pass high-frequency currents of 2000–150,000 cycles/sec. through the bar to be tested.

Permanent Magnets of Iron-Nickel-Cobalt-Aluminium-Copper(-Titanium) Alloys with Preferred Magnetic Orientation. W. Zumbusch. (Archiv für das Eisenhüttenwesen, 1942, vol. 16, Sept., pp. 101–112). The effect of the chemical composition and the heat-treatment on the magnetic properties of permanent-magnet alloys was investigated. The coercivity of certain permanent-magnet alloys can be increased by as much as 160% by cooling in a magnetic field of at least 2000, but preferably 4000 oersted. This applies to iron alloys containing 24–40% of nickel plus cobalt (with a cobalt/nickel ratio of at least 0·8), 7–10% of aluminium, up to 6% of copper, and up to 2% of titanium. The cooling must be from a temperature slightly below the freezing point and the cooling rate must be about 60° C./min. The optimum composition was found to be nickel 14–15·5%, cobalt 21·5–23·5%, aluminium 7·8–9·2%, and copper 3–4%. Up to 1% of titanium can be added, which usually increases the coercive force. The important technical and economic aspects of the production of permanent magnets with preferred magnetic orientation are pointed out and discussed.

New Apparatus for Thermomechanical Study and Micromechanical Testing of Metals. P. Chevenard. (Revue de Métallurgie, Mémoires, 1941, vol. 38, Dec., pp. 317–334; 1942, vol. 39, Feb., pp. 33–53; Mar., pp. 65–83; Apr., pp. 123–128). In the first part of the article the author discusses the symptoms of mechanical hysteresis in metals which are negligible in normal conditions, but increase rapidly at high temperatures and influence considerably Hooke's law. A method is given for calculating the coefficient of expansion, corresponding to each temperature examined, by means of a special apparatus invented by the author. The results of investigations of steel within the 15–450° C. temperature range are presented. In the second part of the article details are given for making micro-tensile, micro-shear, micro-bend and micro-torsion tests and high-temperature creep tests. The Coulomb micro-pendulum and micro-impact tests are also described.

The Elongation Properties of Steels Loaded in Tension at High Temperatures. J. de Lacombe. (Revue de Métallurgie, Mémoires, 1942, vol. 39, Apr., pp. 105–111; May, pp. 152–158; June, pp. 181–188). A description is given of an apparatus which enables the time-elongation curves at high temperatures to be obtained. Tests were made with specimens of low-carbon steels, and chromium-molybdenum, molybdenum, and austenitic nickel-chromium steels loaded in tension at temperatures in the 383–800° C. range. The magnification of 500 allowed the changes in length of the order 10^{-3} to 10^{-5} mm. to be photographically recorded. In each case the period of test was chosen so that the total elongation never exceeded 1% or 2%, the usual limits were 0·1–0·4%. The resulting curves were subjected to a mathematical analysis to examine the possibility of extrapolating the results obtained up to 10,000 hr. The last section of the article deals with the temporary variations of load and the classification of deformations.

"T.R." Machine for Mechanical Testing of Metals at High Temperatures. P. Chevenard. (Revue de Métallurgie, Mémoires, 1942, vol. 39, Nov., pp. 321–330; Dec., pp. 353–359). A detailed description is given of a machine, which (*a*) allows the elongation of a creep-test specimen to be magnified 1000 times and recorded, or (*b*) automatically adjusts the load on the extended specimen and produces a load-time diagram. The small dimensions of the tensile test-piece (4 mm. in dia. × 32 mm. long) allow a light testing machine weighing about 200 kg. with a maximum load of 10 kg. to be used.

The Effect of Titanium on the Creep Strength of Steel. P. Bardenheuer and W. A. Fischer. (Archiv für das Eisenhüttenwesen, 1942, vol. 16, July, pp. 31–38). A titanium/carbon ratio of 6 to 9 in steels containing up to 0·2% of carbon which had been water-quenched and tempered at 600° C. produced the optimum creep strength at 500° C. The value of the optimum creep strength depended on the carbon content and was highest when the carbon exceeded 0·08%. The range of the above ratio giving the optimum creep strength was widened by chromium additions.

The Effect of Titanium on the Creep Strength of Steels. E. Houdremont and G. Bandel. (Archiv für das Eisenhüttenwesen, 1942, vol. 16, Sept., pp. 85–97). The effect of titanium, of the heat-treatment, and of the contents of carbon, manganese, silicon, chromium, molybdenum and vanadium on the creep strength of steel was investigated. The creep strength in the 400–600° C. range of annealed steels increased steadily with increasing titanium; this is only in part due to the titanium dissolved in the α solid solution. An important factor is the precipitation which is very sluggish during annealing without deformation; this only becomes effective on applying the load in the creep test. This is shown in the time-extension

curves by a high initial and permanent elongation and a low creep rate.

The Scatter in the Determinations of the Creep Strength of Steel in the Air Furnace. H. Esser, S. Eckhardt, and G. Finke. (Archiv für das Eisenhüttenwesen, 1942, vol. 16, July, pp. 1–15). It was found advisable to use air furnaces instead of salt baths for making creep tests at about 500° C. As it was more difficult to maintain a uniform temperature in the air furnaces, extensive tests were carried out to determine the scatter of the results obtained with air furnaces when making creep tests by the German standard method A 117/118 on a low-carbon steel, a chromium-molybdenum steel and a chromium-molybdenum-vanadium steel. The results are presented in several tables and are compared with those obtained when salt baths were used.

Testing the Relationship between the Creep Strength and the Heat-Treatment and Cold-Work of Thin-Walled Tubes. H. Esser, S. Eckhardt, and G. Lautenbusch. (Archiv für das Eisenhüttenwesen, 1942, vol. 16, Oct., pp. 131–135). A suitable form of specimen for creep-testing thin-walled tubes by the German standard method A 117/118 at 500° C. was developed. Details of the specimen and of test data obtained after various heat-treatments are presented and discussed. The steel contained 0·15% of carbon and 0·3% of molybdenum. After 27% cold-reduction in manufacture and no heat-treatment the creep strength was 23 kg./sq. cm. Tempering at 650° C. raised this to 25 kg./sq. mm. Raising the annealing temperature to the normalizing temperature reduced the creep strength to 15 kg./sq. mm. Raising the annealing temperature still further to 1050° C. caused a recovery of the creep strength to 23 kg./sq. mm.

The Diffusion of Carbon and Phosphorus in Steels. H. Cornelius. (Archiv für das Eisenhüttenwesen, 1942, vol. 16, Oct., pp. 147–152). The diffusion of carbon and of phosphorus in seven low-alloy steels and one plain carbon steel at 850° and 930° C. was studied. The diffusion of carbon had no effect on the initial distribution of the alloying elements across the section of the specimens. The diffusion of phosphorus caused the carbon to become unevenly distributed and promoted the migration of the manganese, nickel and chromium (but not molybdenum) into the diffusion medium which was used, namely, ferrophosphorus powder. The mechanism of the diffusion process is discussed in the light of the results obtained.

The Relation between the Sensitivity to Superheating and the Content of Aluminium Compounds in Unalloyed Mild Steel. H. Kornfeld and G. Hartleif. (Archiv für das Eisenhüttenwesen, 1942, vol. 16, Sept., pp. 113–116). The sensitivity to superheating, *i.e.*, the temperature at which local grain-coarsening begins, of three low-carbon aluminium-killed steels was determined by annealing specimens for 30 min. at successively increasing temperatures and cooling in air. In all three cases an increase in the content of aluminium compounds, chiefly alumina, was associated with a marked decrease in the grain-coarsening temperature, but neither the total aluminium content nor the amount of metallic aluminium affected this temperature. The determination of aluminium compounds in steel by spectro-analysis is described.

The Properties of Steels Containing up to 5% of Chromium. H. Cornelius. (Archiv für das Eisenhüttenwesen, 1942, vol. 16, Nov., pp. 173–186). An investigation is described in which the effects of the carbon, silicon, manganese, molybdenum, nickel and vanadium contents on the hardenability, tensile strength and impact strength at room temperature and down to — 70° C. were studied. The results are presented in numerous tables and series of curves.

Cold Finished Bars to Physical Property Specifications. M. N. Landis. (Metal Progress, 1945, vol. 48, Oct., pp. 769–777). The differences in the properties of hot-rolled bars before and after cold-drawing are discussed and tables and curves are presented illustrating these differences.

Aircraft Engine Metallurgy Since World War I. W. E. Jominy. (American Society for Metals: Steel, 1945, vol. 117, Nov. 5, pp. 128–129, 192–199). Advances which have been made in the period 1918 to 1939 in the application to aircraft engines of the following materials and processes are discussed: Magnesium, sodium, silver, beryllium, stainless steel, selenium, chromium plate, sintered carbides, forged aluminium, nitriding, grain-size control, hardenability testing and Magnaflux testing.

Conditions Affecting the Quality of Steel for Cold-Heading Dies. A. S. Jameson. (Steel, 1945, vol. 117, Oct. 29, pp. 98–101, 121–122). A method of relating the quality of steel for cold-heading dies to the structure as revealed by a deep-etch test in hydrochloric or sulphuric acid is described. It was found impossible to relate the die life to the estimated number of inclusions.

Corrosion Resistance of the Stainless Steels. C. A. Zapffe. (Metal Progress, 1945, vol. 48, Oct., pp. 693–707). Factors affecting the corrosion resistance of stainless steels are discussed. The type numbers and analyses of stainless steels drawn up by the American Iron and Steel Institute and the (American) Alloy Casting Institute are given. The effect of heat-treatment and of elements other than nickel and chromium on the properties of stainless steels are pointed out. Molybdenum expands the passivity range and improves the resistance to sulphuric acid and neutral chloride solutions including sea water; copper also increases the resistance to sulphuric acid.

Stainless Steels for Turbine Blading. J. H. G. Monypenny. (Institute of Marine Engineers: Engineering, 1945, vol. 160, Nov. 23, pp. 432–433; Nov. 30, pp. 458–460; Dec. 7, pp. 478–480. Iron and Coal Trades Review, 1945, vol. 151, Nov. 23, pp. 803–805, 812; Nov. 30, pp. 855–857). The history of the development of stainless iron for turbine blading and materials with greater resistance to corrosion, particularly the austenitic steels, are described. Data on the corrosion resistance and fatigue properties at room temperature and at high steam temperatures are presented and discussed.

METALLOGRAPHY AND CONSTITUTION

Trends in Metallurgy. G. W. Pirk. (Wire and Wire Products, 1945, vol. 20, Oct., pp. 758–770, 797). The theory of physical metallurgy is explained, the author dealing in turn with the Periodic Table, body- and face-centred lattice structures, the effects of deformation, structural differences from the surface to the centre of drawn wire, effects of alloying elements, and solid solutions.

The Supermicroscopic Reproduction of Metal Surfaces by the Replica Process without Damaging the Metal Surface. V. Duffek and H. Mahl. (Archiv für das Eisenhüttenwesen, 1942, vol. 16, Aug., pp. 73–76). A technique is described for removing synthetic-resin replicas from the surface of metallographic specimens for examination with the electron microscope. The specimen is made the cathode in the non-corroding electrolyte which is used and the replica comes off in less than 1 sec. after hydrogen begins to form. With this process many replicas can be prepared from the same surface without damaging it.

Revealing Phosphorus Segregation by Prints on Cellophane. H. Grubitsch and P. Warbichler. (Archiv für das Eisenhüttenwesen, 1942, vol. 16, Aug., pp. 77–79). A modification of Niessner's method of making phosphorus prints is described. Niessner's method is based on the reduction of the $(NH_4)_3PO_4.12MoO_3$ complex with tin-chloride solution. The prints are made on cellophane.

The Use of Cellophane in M. Neissner's Oxide Print Process. H. Grubitsch. (Archiv für das Eisenhüttenwesen, 1942, vol. 16, Aug., pp. 79–80). Niessner's printing method for revealing oxide inclusions in steel has already been described by H. Dienbauer (*see* Journ. I. and S.I., 1937, No. II., p. 93 A). In the present paper a process of preparing the prints on cellophane is described with examples of some of the results obtained.

The Metallographic Indication of Lead in Steel. K. E. Volk. (Archiv für das Eisenhüttenwesen, 1942, vol. 16, Aug., pp. 81–84). The possibility of revealing lead-bearing inclusions in steel is discussed and a method is described based on the formation of yellow lead iodide at the places where lead occurs. A printing process using paper soaked in acetic acid and then converting the lead acetate into yellow lead sulphide is also described.

A Temper-Etching Process for Distinguishing between Ferrite, Austenite and Carbides in the Structure of High-Chromium Steels. H. Kessner. (Archiv für das Eisenhüttenwesen, 1942, vol. 16, Oct., pp. 145–146). A simple process for distinguishing between ferrite and austenite in chromium-nickel and chromium-manganese steels high in chromium is described. The polished specimen is etched in boiling hydrochloric acid and exposed in air at between 500° and 700° C. until temper colours form on the etched surface. The austenite is clearly defined by the dark brown to violet colour, whereas the ferrite is light yellow. The carbides remain white.

New Intensity Table for the X-Ray Penetration of Iron and Steel. J. Urlaub. (Archiv für das Eisenhüttenwesen, 1942, vol. 16, Oct., pp. 137–142). The sensitivity of films and the intensifying factor of screens have increased in recent years, necessitating the setting up of new intensity data. This has been done for soft carbon steel, and series of curves are presented in which the specimen thickness is plotted against the distance (on a logarithmic scale) of the film from the X-ray tube. The curve for each particular voltage across the tube is practically a straight line.

Magnetic Particle Detection of Retained Austenite and Carbide Segregation. R. J. Dooley. (Iron Age, 1945, vol. 156, Oct. 25, pp. 46–49). The application of the Magnaflux tests to determine segregation and areas of retained austenite in high-speed steel tools is discussed. The method proved to be successful with the molybdenum-chromium-tungsten-vanadium steel tested and its application to the testing of longitudinal sections of bar stock to provide a rapid and accurate indication of the quality is recommended.

Direct Evidence of Solubility of Iron Oxide in Pure Solid Iron. R. Castro and A. Portevin. (Revue de Métallurgie, Mémoires, 1942, vol. 39, Aug., pp. 225–232). Conditions of deformation of iron-oxide inclusions are discussed in connection with changes of their plasticity and solubility in solid hot iron. This solubility is proved by the microscopic examination, particularly by heating up the polished specimens in a vacuum and by observation before and after heating. It is shown how the changes in plastic deformation may lead to the misinterpretation of the micrographs.

The Nature of Martensite. L. Guillet. (Revue de Métallurgie, Mémoires, 1942, vol. 39, Jan., pp. 12–19). The author reviews the theories on the formation and constitution of martensite, and presents the results of his own investigations. Martensite is a supersaturated solid solution of iron carbide in α-iron and its great hardness may be explained by the distortion of its lattice caused by atoms of carbon.

The Solubility of Titanium Carbide and Its Effect when Hardening and Heat-Treating Steel. E. Houdremont, F.-K. Naumann, and H. Schrader. (Archiv für das Eisenhüttenwesen, 1942, vol. 16, Aug., pp. 57–71). Two carbides occur in the Fe–Ti–C system, the easily soluble iron carbide Fe_3C and the titanium carbide TiC which is difficult to dissolve. The former disappears when the titanium/carbon ratio exceeds 4. The solubility of the latter appears to change with different titanium and carbon contents in the steel. With high titanium contents there are two forms of titanium carbide, a primary coarse precipitate and a finely divided form precipitated out of the γ-iron. The results of numerous tests on steels containing up to 3·7% of titanium are presented and discussed.

CORROSION OF IRON AND STEEL

Corrosion of 18-8 Alloy Furnace Tubes in High-Temperature Vapor Phase Cracking Service. E. Q. Camp, C. Phillips, and L. Gross. (Corrosion, 1945, vol. 1, Sept., pp. 149–160). The results of laboratory investigations indicate that the corrosion experienced in the 18/8 stainless steel tubes in the naphtha circuit of the superheater furnaces at a butadiene plant can be eliminated by adding either 0·05–0·5% by weight of sulphur (as free sulphur, carbon disulphide, or butyl mercaptan), or a minimum of 0·06–0·4% by weight of water to the naphtha charge. Carbon dioxide, ethyl alcohol and acetic acid are also satisfactory inhibitors for suppressing this type of corrosion, but their value is not so well established as that of sulphur compounds and water.

Corrosion-Resistant Sucker Rods. (Corrosion, 1945, vol. 1, Sept., p. 148). After six years of exposure in an oil well of a corrosive nature, sucker rods of S.A.E.-4620 steel, plated with 0·006 in. of nickel, were found to be in excellent condition. In a corrosive brine well the nickel coating was perforated by friction, but there was no indication of undercutting or of intense galvanic action, probably because of the absence of oxygen.

Use of Zinc for Cathodic Protection. H. W. Wahlquist. (Corrosion, 1945, vol. 1, Sept., pp. 119–147). The use of zinc as a current source in cathodic protection is discussed. The character of corrosion products on zinc anodes buried in different soils was investigated, and extensive data obtained in tests on zinc-protected buried pipe-lines of the Colorado Interstate Gas Company are presented and analysed.

The Examination by X-Rays of the Oxide Films Formed on Iron at High Temperatures. J. Bénard. (Comptes Rendus, 1943, vol. 217, pp. 77–78). It has previously been shown that if the layer of ferrous oxide which is formed by heating iron in air at 900° C. is removed and reheated at 900° C. it transforms rapidly into ferric oxide. In the present paper the mechanism of this transformation is studied by reference to the lattice parameters of FeO at increasing depths in a 0·5-mm. layer of the oxide.

BOOK NOTICE

TAYLOR, A. "*An Introduction to X-Ray Metallography.*" With a foreword by Sir Lawrence Bragg, O.B.E., F.R.S. 8vo, pp. xi + 400. Illustrated. London, 1945: Chapman and Hall, Ltd. (Price 36*s.*)

In spite of its attractive title, this book will be of more use to the experienced specialist than to the student reading for a degree or to the industrial research worker. It contains a lot of useful information, but unfortunately the book is not well arranged, and the index is inadequate. It is, however, reassuring to find from Chapter I. that the author does appreciate the limitations of X-ray analysis, and states that over-enthusiasm amongst some X-ray workers has led them to overlook the fact that many of the results they have obtained could have been achieved almost as readily by the more conventional methods of metallographic practice.

Chapter II., which deals with X-ray generating apparatus, is moderately complete, but the author devotes only two lines to tubes of the gas type, in spite of the fact that a considerable amount of useful work is being done with them. Chapters III. and IV. are devoted to the space lattice and the diffraction of X-rays by the crystal lattice respectively, and both are well written, and the diagrams are particularly clear and understandable.

The bad arrangement of the book becomes particularly obvious in Chapter V., which is entitled "Experimental Methods of Obtaining Diffraction Patterns." This is a mixed chapter, and whilst describing certain of the experimental methods of obtaining diffraction patterns, contains other miscellaneous paragraphs. The sixth section of this chapter, which is very short, is devoted to "The Identification of the Spectra on the Powder Photograph." This is followed by sections entitled "Typical Cylindrical Debye-Scherrer Cameras," "The Bradley 19 cm. Diameter Camera" and several other sections that quite properly fall into a chapter dealing with experimental methods of obtaining diffraction patterns. Later in the chapter, however, there is a section devoted to the measurement of the film, the elimination of systematic errors from the lattice parameter determination and to applications to non-cubic crystals. These seem to be out of place in this chapter.

Chapter VI. deals with the influence of the atomic pattern on the intensities of the X-ray reflection and with methods for the measurement of the intensities of the lines on powder photographs. It does not, however, indicate what conclusions one may draw as the result of such measurements.

Chapter VII. is a particularly good chapter, and deals very clearly with the Bohr classification of the elements and the crystal structures of metals in general.

Chapter VIII. is devoted to the study of thermal equilibrium diagrams by X-ray methods, and by itself is good, but, unfortunately, even with the help of the preceding seven chapters and the appendix at the end of the book, it is not sufficient to enable a student or a research worker to apply X-ray methods to such a complicated problem as the establishment of an equilibrium diagram.

After chapters dealing with the measurement of grain size, grain orientation and the application of X-rays to the study of refractory materials, the work concludes with a chapter devoted to radiography and micro-radiography. The section devoted to micro-radiography is, as is common with books or papers dealing with this subject, illustrated by the only micro-radiographs that ever appear to have been taken, namely, those obtained from G. L. Clark's contribution to "Photo Technique."

There are numerous tables in the appendix, but it is to be feared that they will be of little, if any, use to anyone whose knowledge of the application of X-ray analysis to metallography is confined to a study of this present work.

J. FERDINAND KAYSER.

FUEL

(Continued from p. 2 A)

The Flow of Gases through Beds of Coke and Other Granular Materials. J. Hiles and R. A. Mott. (Fuel in Science and Practice, 1945, vol. 24, Sept.-Oct., pp. 135–142; Nov.-Dec., pp. 158–171). The influence on the resistance to the flow of gases through beds of coke of varying depth and voidage, of varying particle size over a wide range, and of the effect of the bed temperature, the physical properties of the flowing gas and its velocity through the bed are discussed, and calculations concerning these effects are explained. The effect of all these variables can be combined in a single simple formula which is presented together with examples of its use.

The Control of Gas-Fired Furnaces and the Evaluation of Their Efficiency. W. Callenberg. (Giesserei, 1943, vol. 30, May, pp. 121–129). Detailed descriptions are given of methods of measuring the calorific value, pressure and flow of fuel gases, and the temperature of furnaces. Methods of presenting and co-ordinating the data obtained and maintaining efficient fuel control are discussed.

Present Problems of Heat and Energy Economy in Industry. W. Callenberg. (Giesserei, 1943, vol. 30, Sept., pp. 209–214). In June 1942 a regulation in Germany compelled companies consuming more than 200,000 kWh. of electricity, or 100,000 cu. m. of gas, or 500 tons of coal per month to employ an " energy engineer." The problems confronting this engineer and measures taken to ensure the most efficient use of fuel at large plants are discussed in this paper.

The Training of Heaters. L. T. Pearsall and I. L. McHugh. (Iron and Steel Engineer, 1945, vol. 22, Nov., pp. 59–61). Efficient heating is largely dependent on the skill and experience of the furnace operator, whose training should therefore be closely supervised from the beginning. In spite of the many improvements in automatic control of continuous furnaces, there are still opportunities for improving the intelligent operation of furnaces. Recommendations on the training of furnace-men are made.

Some Simplified Heat Transfer Data. Margaret Fishenden and O. A. Saunders. (Journal of the Institute of Fuel, 1945, vol. 19, Dec., pp. 62–71, 74). Industrial waste-heat recovery involves heat-transfer problems of almost every type. Heat-transmission problems are difficult because of the gap between the conditions of practice and those under which controlled measurements are carried out. Thus the basic data usually obtained for certain simple geometrical arrangements and under defined conditions are not applicable to the much more complicated design and conditions of actual plant. Consequently assumptions and approximations have to be made which entail errors. In this paper, however, some basic data are presented in more easily usable form for the benefit of the practical designer. Actual heat-transfer coefficients can be read off directly from curves for some of the most important cases.

The Utilization of Waste Heat in High-Temperature Carbonization Processes. H. D. Edwards. (British Coal Utilisation Research Association, Bulletin, 1945, vol. 9, Dec., pp. 333–338). The scope for waste-heat recovery in carbonizing processes is outlined and the recovery of sensible heat in flue gases, coke, and volatile matter discussed. From a study of the literature (28 references are given) it is concluded that there are many methods of waste-heat recovery which ought to be applied in order to conserve British fuel resources.

The Use of Centrifugal Force for Cleaning Fine Coal in Heavy Liquids and Suspensions with Special Reference to the Cyclone Washer. M. G. Driessen. (Journal of the Institute of Fuel, 1945, vol. 19, Dec., pp. 33–45). A scientific investigation has shown that, in coal-washing, settling times increase very rapidly with decreasing size of the particles. Similarly, the time required for the separation of coal and shale in a dense medium increases rapidly with decreasing size. Separation using true liquids entails great practical difficulties—especially with fine coals. This is due to the large amount of liquid which adheres to the washed products. Separation using suspensions instead of true liquids is to a much greater degree necessary with fine coal than with nuts. But the high viscosities and yield-point values of suspensions prevent an economic separation if using only the force of gravity. Hence recourse has to be made to the use of centrifugal force which can be made 2000 times as great as gravity. The cyclone washer described is a simple centrifugal washer which allows continuous operation, and no mechanical means are required to remove the washed products. True liquids and suspensions can be used.

Coke-Oven and Blast-Furnace Plants. J. H. Patchett. (Cleveland Institution of Engineers: Iron and Coal Trades Review, 1945, vol. 151, Dec. 21, pp. 979–984, 996). Progress in the design and operation of coke-ovens and blast-furnaces is reviewed. It appears that the limit in oven capacity has been reached and that future development will be in the design of a more robust furnace structure. The use of sinter is discussed and the efficiencies of the turbo-blower and the gas-engine-driven blower are compared.

Contribution to a Study of Blast-Furnace Coke. C. G. Thibout. (Révue de Métallurgie, Mémoires, 1943, vol. 40, May, pp. 129–142). Results are presented of tests carried out in the Longwy district in France, where various kinds of coke were tried in blast-furnaces during the war. The physical and chemical properties of coke are examined and a coefficient for expressing coke quality is suggested.

Shale Oil. (Engineer, 1945, vol. 180, Dec. 21, pp. 498–500; Dec. 28, pp. 520–521). The shale oil industry in the British Empire is reviewed, and descriptions are given of the Salermo retort and the Davidson rotary retort for the carbonization of shale and torbanite (a material intermediate between shale and coal which contains more hydrogen than coal).

PRODUCTION OF IRON

(Continued from pp. 2 A–3 A)

Moving the Pembroke Blast-Furnace from Florida to Texas. R. H. Sweeter. (Iron Age, 1945, vol. 156, Nov. 15, pp. 66–67). A description of the removal of a blast-furnace from Pembroke, Florida, to Rusk, Texas, is given.

Slag Wool and Rock Wool as a Universal Substitute Material. H. Schmidt. (Iron and Steel Institute, 1946, Translation Series, No. 264). This is an English translation of a paper which appeared in Stahl und Eisen, 1943, vol. 63, May 6, pp. 360–365 (*see* Journ. I. and S. I., 1945, No. II., p. 131 A).

Producing Sponge Iron in a Rotary Kiln. T. L. Johnston. (Steel, 1945, vol. 117, Nov. 12, pp. 128–129, 140–142). An account is given of experimental work by the United States Bureau of Mines in making sponge iron in a rotary kiln at Laramie, Wyoming. The sloping kiln is 80 ft. long, 6 ft. in dia. for the upper 50 ft., and 9 ft. in dia. for the remaining 30 ft. The slope is $\frac{1}{2}$ in./ft. The kiln is fired with natural gas or pulverized coal. Under the optimum conditions at least 90% of the iron is reduced to the metallic state. The sponge iron is put through a roll crusher, a centrifugal polishing machine, and a magnetic separator. The product can be used for steelmaking in the granular or briquetted state.

Mechanical Parts Made from Powdered Metals. R. P. Seelig. (Steel, 1945, vol. 117, Nov. 19, pp. 116–119, 156–178). The possibilities and limitations of the powder-metallurgy process are examined and a great variety of parts made by it are discussed. Examples of how slight changes in shape have made a component easily producible by this method are described and illustrated.

FOUNDRY PRACTICE

(Continued from pp. 3 A–4 A)

A Review of the Major Changes in Grey-Iron Foundry Practice During the Period 1914–1944. A. E. McRae Smith. (Institute of British Foundrymen: Foundry Trade Journal, 1945, vol. 77, Dec. 27, pp. 371–377). This is a *résumé* to stress the more important trends of theory and practice (between 1914 and 1944) which have exerted a major influence in establishing the properties and qualities of grey-iron castings at the present high level. The metallurgical side of the grey cast-iron industry has shown much greater progress than has been the case with casting technique. The following are among the subjects dealt with: (1) Development of foundry technique; (2) "semi-steel"; (3) the Thyssen-Emmel and Meehanite processes; (4) Ni-tensyl and acicular cast iron; (5) ladle metallurgy; (6) martensitic irons; (7) melting technique in cupolas and electric furnaces; (8) solidification; and (9) moulding and core-making.

Grey Iron Production for War. J. S. Vanick. (French Foundry Association: Foundry, 1945, vol. 73, Nov., pp. 96–101, 226–236). The change-over from peace-time to war-time production of grey-iron castings by American foundries and the principal war-time developments are described.

Cupola Bed Lighting. J. Timbrell. (Foundry Trade Journal, 1945, vol. 77, Dec. 20, p. 338). A novel method of lighting a cupola, using an oxygen lance with the oxygen at 15 lb./sq. in., is described. Details of the arrangement of wood, coal, and the coke charge, are given. The total time for oxygen projection in the cupola should not exceed 10–12 min. during which 30–40 cu. ft. are used. The fire should be going satisfactorily in 20 min.

Air Weight Control for Foundry Cupolas. R. W. Adams. (Institute of Australian Foundrymen: Australasian Engineer, Science Sheet, 1945, Oct., pp. 6–9). The usefulness of oxygen control in the cupola is emphasized as each stage of combustion is indicated by the percentage of CO_2 in the combustion gases, and the oxygen in the air is used to support combustion. The temperature of the metal depends on the amount of heat developed in the combustion zone, *i.e.*, on the ratio of air to coke. Practical examples are given of methods of blast-volume control using an air-weight instrument which incorporates a standard flow-meter measuring the pressure drop at an orifice plate.

Relative Effect of Lime and Dolomite Fluxes on Cupola Irons and Cupola Operation. C. C. Sigerfoos and H. L. Womochel. (American Foundryman, 1945, vol. 8, Oct., pp. 68–71). This report describes experiments performed to determine the effect of substituting dolomite for limestone as a cupola flux. Data are presented to show the effect of the slags on the sulphur, carbon, silicon, phosphorus, and manganese contents of the iron.

Cupola Slag. O. Glaser and F. Roll. (Giesserei, 1943, vol. 30, Feb. 5, pp. 37–43). The composition, structure, properties, and application of cupola slags are discussed.

The Effects of Slag on Cast-Iron Melts. P. Bardenheuer. (Mitteilungen aus dem Kaiser-Wilhelm-Institut für Eisenforschung: Giesserei, 1943, vol. 30, July, pp. 161–166). The reactions between metal and slag in the open-hearth furnace and in the cupola are discussed with special reference to desulphurization.

The Hot-Blast Cupola at Aachen. E. Piwowarsky. (Giesserei, 1943, vol. 30, Oct., pp. 221–225). The hot-blast cupola at the Giessereiinstitut at Aachen is described and illustrated (*see* Journ. I. and S. I., 1939, No. II., p. 9 A) and operating data and heat balances are presented. Very good results were

obtained with a blast temperature of 450–600° C.; in fact, with blast temperatures of 300° and 600° C. reductions of 18·4% and 36·3%, respectively, in the coke consumption were obtained and the casting properties of the iron were improved.

Operating Experience with the Hot-Blast Cupola. M. Bader. (Giesserei, 1943, vol. 30, Nov., pp. 241–246). The results of experiments by E. Piwowarsky with a hot-blast cupola (*see* preceding abstract) have been applied at a Schaffhausen foundry where four cupolas with diameters of from 700 to 900 mm. have been in operation from 1941 to 1943. These cupolas have been blown with air heated in Schack recuperators up to 600° C. and have shown very great economy in coke consumption. Several thousand tons of iron for malleable castings have been made. The iron was lower in sulphur than formerly and had greater tensile strength and a higher elastic limit with the same elongation. Detailed results of tests on the coke consumption at different blast temperatures are presented and discussed.

Collectors on Cupolas Clean Waste Gases. A. H. Allen. (Foundry, 1945, vol. 73, Nov., pp. 88–90, 199–200). A detailed description is given of the dust collectors which were fitted to the tops of six 8-ft. dia. cupolas at a Michigan foundry. The collector carries water-spraying equipment through which the cupola gases emerge.

Foundry Research in the Chilled Car Wheel Industry. E. Bremer. (Foundry, 1945, vol. 73, Nov., pp. 112–114, 264–265). Methods of producing chilled railway wagon wheels, in particular the cooling procedure, developed by the Association of Manufacturers of Chilled Car Wheels, are described and discussed.

The Production of Grey Iron Castings by the Metal-Mould Process. C. Englisch. (Giesserei, 1943, vol. 30, Aug., pp. 181–189). The technique for making grey-iron castings in metal moulds, with special reference to making cylinders for air compressors and hydraulic brakes, is discussed in detail.

Notes on the Metallurgical Treatment of Malleable Cast Iron. G. Brinkmann and P. Tobias. (Giesserei, 1942, vol. 29, Oct. 16, pp. 356–588). The advantages and disadvantages of different melting processes for the preparation of iron for malleable castings are discussed. The processes examined include those using cupolas and reverberatory, open-hearth, Brackelsberg, and arc furnaces.

The Electric Furnace in the Steel Foundry. H. Stephenson and G. R. Stanley. (Australasian Engineer, Science Sheet, 1945, Oct., pp. 12–19). An illustrated review is presented of the design and operation of acid and basic high-frequency furnaces and acid and basic three-phase arc furnaces. The advantages and disadvantages of each type are discussed and the reasons for the increasing popularity of the electric furnace are given.

Bessemer Shop Practice. R. Stolle. (Giesserei, 1942, vol. 29, Dec. 11, pp. 413–419). The cupola/Bessemer process of making cast steel is discussed with special reference to factors affecting the efficiency of the operation of the converter. Methods of calculating the ferrosilicon and ferromanganese additions are also dealt with.

The Technique of Casting Steel. A. Heuvers. (Giesserei, 1943, vol. 30, Sept., pp. 201–209). The principal points in the production of good steel castings are critically examined, with special reference to the causes of cavities and cracks. Several examples of good and bad castings showing the positions of gates and risers are described and illustrated.

Steel Foundries in the Foreign Literature of 1940 and 1941. H. Juretzek and W. Trommer. (Giesserei, 1943, vol. 30, Dec., pp. 261–272). The American, English, and Russian literature for the years 1940 and 1941 on steel foundries is reviewed. The bibliography contains 79 references.

Sand-Control in a Malleable Iron Foundry. G. Davis. (American Foundryman, 1945, vol. 8, Oct., pp. 65–67). A brief discussion of the different sands used for light, medium, and heavy malleable-iron castings is presented.

Split-Type Specimen Tube for Elevated Temperature Sand Testing. D. C. Williams. (American Foundryman, 1945, vol. 8, Sept., pp. 68–72). This is a report by the Sub-Committee on Physical Properties of Steel Foundry Sands appointed by the American Foundryman's Association Committee on Physical Properties of Foundry Sands at Elevated Temperatures. The advantages of using a split tube for forming sand specimens for the hot-compressive-strength test are pointed out.

Determining the Gas-Permeability in the Testing of Moulding Sands—A Note on Standardizing Methods of Testing. W. Reitmeister. (Giesserei, 1943, vol. 30, Aug., pp. 189–193).

The Consumption of New Sand and Sand Binders in the Production of Green-Sand Steel Castings. E. Holweg. (Giesserei, 1943, vol. 30, Mar. 3, pp. 76–80). The author analyses the consumption of the sand used by thirteen German steel foundries and the distances from the sources of supply, and makes recommendations for economies in both consumption and transport.

British Bonding Clays. W. Davies and W. J. Rees. (Journal of the Iron and Steel Institute, 1945, No. II., pp. 117 P–125 P). War conditions made necessary an investigation of the characteristics of indigenous bonding clays which might be suitable to replace, either partly or wholly, imported bonding clays. Typical examples of the three main groups of bonding clays have been examined, and the range of properties of synthetic moulding sands prepared with them is indicated. Experience has shown that, either alone or in admixture, these indigenous clays can be used successfully in many foundries.

Tests on Various Core Oils and New Core Binding Materials. H. Wellnitz. (Giesserei, 1943, vol. 30, Feb. 19, pp. 53–58). Chemical and physical acceptance tests for core oils are described and the results of bend and permeability tests on a number of core-sand mixtures are presented and discussed. The effect of substituting dextrine for a proportion of the core oil normally used is shown.

Core Oils and Core Binders. K. Hüttenes. (Giesserei, 1942, vol. 29, Dec. 11, pp. 419–422). The preparation and properties of cores, in particular the

admixture of oil and binding compounds and their effects, are discussed.

Procedure for Testing Dry Binders. F. Roll and Annemarie Arland. (Giesserei, 1944, vol. 31, July, pp. 110–113). Methods of testing core-binding materials such as sulphite lye, starch, dextrine, pitch, and clay developed by the "Core-Binder" Sub-Committee of the Verein deutscher Giessereifachleute are described.

The Composition and Testing of Core Binders. F. Roll and Annemarie Arland. (Giesserei, 1943, vol. 30, Dec., pp. 272–275). There were about 200 core binders on the market in Germany in 1942, when steps were taken to reduce this number and to economize in the use of linseed oil. In this paper details are given of the standard classification which was drawn up to meet this need. The requirements of cores and of core-binding materials and methods of testing them are also discussed.

Physical Testing of Core-Binding Materials. C. E. Schubert. (Foundry, 1945, vol. 73, Nov., pp. 91, 192, 195, 199). The making and testing of cores are described. In particular, details are given of the tensile test at room temperature and at 250° F., of the determination of the amount of gas given off by the binder and of the loss in strength when exposed in a very humid atmosphere.

Synthetic Foundry Sands with Cement as a Binder. K. Endell and W. Strasmann. (Giesserei, 1942, vol. 29, Oct. 16, pp. 349–356). After a review of the literature on the use of cement as a binder in moulding sand, with special reference to American experience, an investigation is reported in which the effects of the amounts of cement and moisture in the synthetic sand on its shear strength and permeability were studied using three German cements. There is an optimum moisture content for each cement which has to be adjusted according to the time at which the maximum strength is required. Ordinary Portland cement requires exceedingly little moisture for the mould to attain a high strength after 1–3 days setting time. Much more water is necessary with better quality cement.

The Possibilities of Using Plastics as Core Binders and Their Success in Practice. K. Grassmann. (Giesserei, 1943, vol. 30, Nov., pp. 246–253). In seeking a substitute for linseed oil for binding core sands extensive tests were made with synthetic materials, and the results obtained are reviewed.

Coal Dust for Moulding Purposes. F. Roll. (Giesserei, 1942, vol. 29, Oct. 30, pp. 371–374). The addition of coal dust to moulding sand and its effect on the surface of the casting are discussed. The results of tests on twenty-one mixtures showing the effect of the quality and particle size of the coal are presented. A specification for coal dust drawn up by the Verein deutscher Giessereifachleute is given.

The Effect of Moisture in the Sand on the Formation of Subcutaneous Blowholes in Ni-Hard (BF954) Castings. (Bradley's Magazine, 1945, Dec., pp. 3–4). An investigation to determine whether a high moisture content of the sand was the cause of blowholes in Ni-Hard iron castings is reported. Moisture in the sand did not seem to affect the size or incidence of the blowholes, which are probably caused by a gas dissolved in the liquid metal thrown out during solidification. A very moist sand causes a chilling effect which makes the surface layer hard and rigid. In a cast plate, the principal dimensions of which differed widely, there were no blowholes at all, but the less the three dimensions differed the larger were the blowholes which appeared.

Tellurium Corewashes. J. O. Vadeboncoeur. (American Society for Metals, Oct., 1945, Preprint No. 31). The application of core-washes containing tellurium to grey-iron foundry practice is discussed. The mechanism of entry into the metal from the core-wash appears to be a diffusion action of either tellurium or tellurium-oxide vapour, and the effect is to stabilize the iron carbide at the core-metal interface. Methods of preparing the core-wash are described.

The Technological Principles of Casting Design. V. M. Shestopal. (Foundry Trade Journal, 1945, vol. 77, Dec. 13, pp. 317–322; Dec. 20, pp. 339–346). Recommendations for simplifying casting design are made and some of the standards adopted in the U.S.S.R. for draft and contraction are cited.

A New Method of Feeding Applied to Castings Made in Static Moulds. S. T. Jazwinski and S. L. Finch. (Foundry Trade Journal, 1945, vol. 77, Nov. 29, pp. 269–274; Dec. 6, pp. 293–303). The development of a method of applying pressure to the feeder head for steel castings in order to increase the yield of castings from the total weight of steel melted is described. The method is called "gas pressure feeding." It consists of introducing into the feeder head before casting, a charge of material adapted, after a surface skin or envelope of solid metal has formed in the feeder head by cooling, to create a gas, the pressure of which will act upon the liquid metal to force it into the mould. An exothermic composition such as a mixture of iron oxide and aluminium can also be introduced to supply heat to compensate for conduction and radiation losses. The two factors pressure and heat result in a globular cavity with a meniscus inside the feeder head. A suitable compound called "Kayell" has been developed. The method of fixing the Kayell in the feeder head and means of delaying the action of the gas pressure are described with illustrations of sections of solidified feeder heads showing the cavities formed under different conditions.

Precision Casting with Plastic Patterns. C. T. Post. (Iron Age, 1945, vol. 156, Nov. 15, pp. 54–59). The question of dimensional accuracy in the lost-wax precision-casting process in conjunction with reproducibility on longer production runs, has entailed research into pattern materials and some difficulties have been overcome. Injection-moulded polystyrene patterns do not perish as do wax patterns; moreover, the former give high dimensional accuracy, smooth finish and improved reproducibility.

On Casting-On Processes, Especially for Copper Alloys on Steel. G. Kritzler. (Giesserei, 1943, vol. 30, Apr., pp. 101–106). The theory of joining one metal to another by mechanical means, adhesion, and diffusion is explained and the diffusion of copper in steel is studied in detail.

The Centrifugal Casting of Iron and Steel. W. A. Geisler. (Giesserei, 1943, vol. 30, Oct., pp. 225–234). A number of patented processes for the centrifugal casting of pipes, bushes, cylinders, gear-wheels and gun-barrels in iron and steel are described and illustrated.

Malleable Foundry Design. (Foundry, 1945, vol. 73, Nov., pp. 102–104, 156). A description of the plant and processes at a new malleable-iron foundry of the General Motors Corporation has already been given (*see* Journ. I. and S. I., 1945, No. II., p. 4 A). In the present paper the lighting, ventilation, and construction of the buildings are briefly described.

Navy Yard Foundry Meets Peak Demands. P. Dwyer. (Foundry, 1945, vol. 73, Oct., pp. 106–109, 180–188). A description is given of the large and highly mechanized foundry at the Philadelphia Navy Yard.

Ventilating Equipment in Iron and Metal Foundries. G. Zweiling. (Giesserei, 1943, vol. 30, Feb. 19, pp. 58–60).

PRODUCTION OF STEEL

(Continued from pp. 4 A–5 A)

Iron and Steel in the U.S.S.R. L. Evans. (Iron and Coal Trades Review, 1945, vol. 151, Dec. 14, pp. 931–933). The impressions formed during a visit to the Magnitogorsk and other works are reported, with notes on the coal, coke and refractories used, the furnaces and mills, the management, the labour and the working conditions.

Russia Recovering. R. A. Davies. (Iron and Steel, 1945, vol. 18, Nov. 30, pp. 525–530). An account is given of progress made in the reconstruction of Russian iron and steel works which were destroyed during the war.

Liquid Fuel Firing of Open-Hearth Furnaces. C. Wales. (Man and Metal, 1945, vol. 22, Dec., pp. 138–139). It is recommended that greater consideration be given in Great Britain to the firing of open-hearth furnaces with fuel oil or tar. Burners have been designed to take from 3 to 10 gal./min. A burner or "gun" at each end of the furnace is preferable to multi-jet systems. The average consumption is $6\frac{1}{2}$ gal./min. for 200–260-ton furnaces, and $4\frac{1}{2}$ gal./min. for 80–100-ton furnaces.

Influence of the Charge upon Open-Hearth Furnaces. H. F. Lesso and R. W. McCann. (Iron and Steel Engineer, 1945, vol. 22, Oct., pp. 37–47). The effect of changes in the materials charged in the open-hearth furnace on the life of the roof was studied by collecting data on the charges of six complete campaigns on furnaces with short roof life and on four campaigns on furnaces with long roof life. In all, 1400 heats were statistically analysed. In particular the influence of the charge on the input of B.Th.U./hr. and on the B.Th.U./ton of steel produced were determined and several series of curves demonstrating these relationships are presented. It was observed that the heat required per ton of steel produced increased steadily with increasing proportions of light scrap up to 22%, above which it decreased rapidly with the furnaces with a short roof life. There is an optimum proportion of pig-iron in the charge for each open-hearth plant which meets the prevailing operating conditions in an especially favourable manner.

Steelmakers Test Usefulness of Electrolytic Manganese. R. T. C. Rasmussen and F. Sillers, jun. (Steel, 1945, vol. 117, Nov. 19, pp. 138–143, 188–191). Full-scale trials in open-hearth and electric furnaces are described in which electrolytic manganese from the Boulder City plant of the Bureau of Mines was used instead of ferromanganese. There was no significant difference in the properties of the steel produced.

Recent Results from Fluidity Tests in the Melting of Chromium-Molybdenum Steels with and without Nickel in Basic Arc and Open-Hearth Furnaces. W. Ruff. (Iron and Steel Institute, 1946, Translation Series, No. 263). This is an English translation of a paper which appeared in Stahl und Eisen, 1943, vol. 63, June 3, pp. 438–442 (*see* Journ. I. and S. I., 1945, No. II., p. 135 A).

Determining Lime-Silica Ratios for Open-Hearth Control by Mathematical Computation Using FeO and Fe_2O_3 Values. J. S. Coulter. (Blast Furnace and Steel Plant, 1945, vol. 33, Oct., pp. 1242–1247). Details are given of a procedure developed by the Jones and Laughlin Steel Corporation for rapidly determining the lime/silica ratio in open-hearth slags. The slags are classified into four groups in accordance with the crystallographic properties and colour of crushed samples. In each group the difference between the FeO and Fe_2O_3 contents is related to the silica content and the total iron is related to the lime content. Formulæ are developed from these relationships which enable the lime/silica ratio to be calculated.

Quality Control Testing of Semi-Finished Bars. E. W. Mahaney and D. W. Lloyd. (Iron and Steel Engineer, 1945, vol. 22, Nov., pp. 48–50). It is shown how statistical methods were applied for the investigation of steel quality, and how a control programme was set up by which the cost of conditioning billets was considerably reduced and the production of defective billets was decreased by 40%.

Practical Application of Statistical Methods in a Quality Control Program. W. T. Rogers. (American Society for Metals, Oct., 1945, Preprint No. 23). An attempt is made to explain in non-technical language how statistical methods are applied to control the quality of the products in various processes in a steelworks. One of the examples given is a study of the correlation of the number of rejected billets to the iron content of the slag, the casting temperature, the ingot reheating time, the mould temperature, and the mould wash.

Effects of Deoxidation Practice. (Steel, 1945, vol. 117, Dec. 3, pp. 114–117, 154). Prolonged service of steel at elevated temperatures depends on the microstructure, and this itself changes throughout the service life. These microstructural changes occurring over longer periods at high temperature have been studied for three carbon and six molybdenum steels. A relationship between spheroidization and graphitization in the presence of the aluminium added for deoxidizing is probable. Tables show how spheroidization and graphitization progress in steel at various temperatures with increasing aluminium additions and with different deoxidation practices.

The Reduction of Silica by Liquid Steel. W. Geller. (Revue de Métallurgie, Mémoires, 1943, vol. 40, June, pp. 183–191; July, pp. 219–224). This is a French translation of a paper which appeared in Archiv für das Eisenhüttenwesen, 1942, vol. 15, May, pp. 479–490 (*see* Journ. I. and S. I., 1945, No. II., p. 184 A).

Note on Oxide Systems Pertaining to Steel-Making Furnace Slags. A. H. Jay and K. W. Andrews. (Journal of the Iron and Steel Institute, 1945, No. II., pp. 15 P–18 P). An X-ray survey has been made of the binary systems FeO–MnO, FeO–MgO, CaO–MnO, and MgO–MnO. All systems show complete solubility at a temperature of 1150° C. The variation of lattice spacings with composition in each system is recorded.

Electric Steel-Making in the Arc Furnace. C. Wissmann. (Electrochemical Society, Oct., 1945, Preprint No. 12). Descriptions are given of the acid and basic processes of making steel in the electric-arc furnace.

Some Thoughts on Experimental Electric Arc Furnace Smelting. H. S. Newhall. (Electrochemical Society, Oct., 1945, Preprint No. 13). Electric-arc furnace design, choice of phase, electrodes, refractories and the operation of experimental steelmaking furnaces are discussed.

Electric Induction Steel "E.I.S." F. T. Chesnut. (Electrochemical Society, Oct., 1945, Preprint No. 17). A review is presented of the present status of the application of the high-frequency induction furnace to steel-melting.

A Thermal Engineer's View of an Arc Furnace. V. Paschkis. (Electrochemical Society, Oct., 1945, Preprint No. 20). Means of increasing the melting efficiency of the electric-arc furnace are considered from the heat-transfer point of view.

Steel-Making ; A Modern Installation of Arc Furnaces. (Electrical Review, 1945, vol. 137, Dec. 7, pp. 809–814). A steelmaking plant comprising three Siemens 15-ton and one 5-ton electrode furnaces and accessory equipment at the works of the Brymbo Steel Company, Ltd., North Wales, is described.

Safety Practices. R. L. Beeswy. (Iron and Steel Engineer, 1945, vol. 22, Oct., pp. 77–80). The safety precautions relating to electrical machinery and circuits, and especially to cranes, at the works of the Inland Steel Company are described.

FORGING, STAMPING, AND DRAWING

(Continued from pp. 5 A–6 A)

World's Largest Hydraulic Presses. (Steel, 1945, vol. 117, Dec. 3, pp. 130–186). A description is given of two hydraulic presses built to forge armour plate, hollow forgings, and shafts for the American Navy. The maximum pressing force is 14,000 tons eccentric load capacity 6 ft. off centre; the working stroke is 10 ft. and the overall height 74 ft. Controls permit the press head to be moved to within $\frac{1}{16}$ in. of any desired position.

Magnetic Core Laminations Produced at Minimum Cost. G. M. Shingledecker. (Machinist, 1945, vol. 89, Dec. 29, pp. 2125–2127). The fabrication of magnetic core laminations is essential for the manufacture of electric motors. All laminations must conform to rigid standards of dimensional accuracy and magnetic performance so that the selection of a good tool steel with correct stamping qualities, the controlled annealing of the laminations to obtain the desired electrical characteristics, and the use of progressive dies of sectional type are necessary for ideal lamination production.

Forging Die Design. J. Mueller. (Steel Processing, 1945, vol. 31, Oct., pp. 633–635). Recommendations are made on the use of inserts in forging dies for mass-production work.

Factors Affecting Die Life. A. S. Jameson. (Steel, 1945, vol. 117, Nov. 26, pp. 101–106). A statistical analysis is made of factors affecting the life of the dies used for cold-heading in the manufacture of bolts with square necks.

Estimating Die Costs. R. Howell. (Iron Age, 1945, vol. 156, Nov. 29, pp. 44–48). The differences which frequently prevail in estimating the costs of forging dies are due in only a small degree to variations in labour and material costs, but may well be the result of faulty or inefficient recording methods. In this article the author presents the costing methods which are employed by a company making large numbers of drop-forgings.

Recent Engineering Developments Contribute to Greater Stamping Production. (Steel Processing, 1945, vol. 31, Oct., pp. 636–638). Examples are given of the manner in which machine-gun mountings and other small ordnance parts were produced in large numbers by improvements to stamping processes.

High Forging Temperatures Revealed by Facets in Fracture Tests. J. R. Strohm and W. E. Jominy. (American Society for Metals, Oct., 1945, Preprint No. 25). The occurrence of large grains or light-coloured facets in the fractures of forged low-alloy steel bars is discussed. They indicate that the forging temperature was too high. The critical temperature below which these facets did not appear was determined for a number of steels.

Forming Tubular Products and Closing Tube Ends by Flame Spinning. (Steel, 1945, vol. 117, Nov. 26,

pp. 92–93). A process of forming the ends of tubes and hollow bodies is described. The tube end is rotated under an oxy-acetylene multiple-tip burner and the closing is done with a hard-faced forming tool or shoe.

Manufacture of Fine Steel Wire and Some of Its War Applications. J. R. Thompson. (American Iron and Steel Institute: Blast Furnace and Steel Plant, 1945, vol. 33, Oct., pp. 1248–1252, 1276, 1277).

Coatings and Lubricants. (Wire Industry, 1945, vol. 12, Nov., p. 575). The characteristics and limitations of lime as a wire-drawing lubricant are discussed.

ROLLING-MILL PRACTICE

The Rolling of Metals: Theory and Experiment, L. R. Underwood. (Sheet Metal Industries, 1945, vol. 22, Aug., pp. 1360–1366; Sept., pp. 1535–1545; Oct., pp. 1719–1724, 1736; Nov., pp. 1905–1913; Dec., pp. 2089–2095). The discussion of the inter-action of roll diameter, dimensions and nature of material, etc., in the rolling of metals is continued in Parts V., VI., and VII., which deal respectively with the factors affecting the yield stress in cold- and hot-rolling, external friction between the rolls and the material, and factors influencing rolling load and specific roll pressure. (*See* Journ. I. and S. I., 1945, No. II., p. 110 A).

Rail and Structural Mill for Volta Redonda Plant Designed for Varied Output. C. Longenecker. (Blast Furnace and Steel Plant, 1945, vol. 33, Sept., pp. 1108–1112). A description is given of the rolling-mill plant which will shortly be put in commission at the Volta Redonda steelworks in Brazil.

Bethlehem Centralizes Bar Mills. (Iron Age, 1945, vol. 156, Nov. 15, p. 77). A continuous high-speed 10-in. merchant bar mill, with a monthly capacity of 22,000 tons in sizes of $\frac{5}{16}$ to $1\frac{1}{2}$ in. rounds at one of the Bethlehem Steel Company's works is described.

Rolling of Large Diameter Tubes. (Machinery, 1945, vol. 67, Nov. 22, pp. 568–570). A mill is described for rolling pierced billets to construct hollow bodies up to 40 ft. long and from 4 to 6 ft. in dia.

Electric Equipments for a 16-Stand Tube Mill. A. L. Thurman. (Blast Furnace and Steel Plant, 1945, vol. 33, Oct., pp. 1235–1241, 1247). Descriptions of modern tube-reducing mills are given. An example is a 16-stand mill with the stands only $12\frac{1}{2}$ in. apart. This is capable of reducing $4\frac{1}{2}$-in. dia. tubing down to $\frac{3}{4}$ in. in dia., the exit speed being 300 to 500 ft./min.

The Manufacture of Butt-Welded Pipe. N. W. Richardson. (Iron and Steel Engineer, 1945, vol. 22, Nov., pp. 64–68). The Fretz-Moon process of making pipes by continuous butt-welding and the requisite plant are described and illustrated. Important advantages are reduced costs of operation and maintenance, and higher yield and quality. Mills of this type are in operation in the United States, England, Australia, Russia, Germany, and Canada.

Improving Production in the Finishing Shop of a Plate Mill by Work- and Time-Studies on the Straightening Rolls. Part II. E. Kratschmar. (Archiv für das Eisenhüttenwesen, 1942, vol. 16, July, pp. 39–44). Continuation of a previous article. (*See* Journ. I. and S. I., 1943, No. II., p. 82 A).

Work-, Time-, and Cost-Studies, Explained by the Example of the Cutting of Plates with Hydraulic Shears. Part III. E. Kratschmar. (Archiv für das Eisenhüttenwesen, 1942, vol. 16, Sept., pp. 117–127). Conclusion of a series of articles (*see* preceding abstract).

Rolling Mill Guides. W. F. Hoffman. (Iron and Steel Engineer, 1945, vol. 22, Nov., pp. 69–79). Problems in the design of entry and exit guides for rolling mills are discussed and many designs of guides are described and illustrated.

Cooling Beds and Transfers. C. L. Raisig. (Iron and Steel Engineer, 1945, vol. 22, Nov., pp. 37–47). Several modern cooling beds for rolled bars are described in detail and the requirements for an efficient bed are discussed. They should be flexible enough to meet all operating demands. Useful data are given correlating the dimensions of various sections and the cooling times required.

Electronic Controls. F. Roberson. (Iron and Steel Engineer, 1945, vol. 22, Oct., pp. 59–61). Some applications of electronic devices for controlling machinery in the iron and steel industry are described and illustrated.

Rectifiers in the Steel Industry. F. Mohler. (Iron and Steel Engineer, 1945, vol. 22, Oct., pp. 66–74). The theory of current rectifiers is explained with descriptions of phanotron or thyratron, ignitron, and metal plate rectifiers and their applications in the steel industry.

Continuous Gaging with X-Ray Micrometer. R. C. Woods and F. Fua. (Iron Age, 1945, vol. 156, Nov. 29, pp. 50–51). The thickness of sheet in motion can be gauged with high sensitivity by a device which combines X-rays and electronic instruments. The method described can be applied to measure the wall thickness of long metal tubes at any point, and in the case of coated metals the thickness of the coating and that of the base metal can be measured independently.

PYROMETRY

Some Practical Aspects of Pyrometry. R. G. Ackland. (Australian Institute of Metals: Australasian Engineer, Science Sheet, 1945, Sept. 7, pp. 9–16). The theory and practice of pyrometry is surveyed with descriptions of thermocouples, millivoltmeters, potentiometric instruments, optical pyrometers and methods of checking instruments.

Pyrometry. H. J. Smith. (Metal Industry, 1945, vol. 67, Dec. 14, pp. 395–397; Dec. 21, pp. 415–417). Developments in the design of new pyrometric

equipment and its application to industrial plant during the last six years are reviewed.

The Design and Performance of Some Commercial Optical Pyrometers of the Disappearing-Filament Type. C. R. Barber. (Journal of the Iron and Steel Institute, 1945, No. II., pp. 171 P–188 P). A critical examination has been made of five models of commercial portable optical pyrometers of the disappearing-filament type, with reference to the design of the lamp, the optical system, the monochromatic and neutral filters, and the measuring system.

It has been shown that in many cases the lamp filaments are too short to be free from end-effect, and the advantages of the use of a flat-filament in this and other respects are discussed. The size and position of the diaphragms of the optical system were in some examples not in accordance with those necessary for obtaining perfect disappearance of the filament. The transmission curves of the monochromatic and neutral filters are given, and the requirements of the combination of the two filters are examined. A current or voltage calibration of the lamp may be employed and the advantage of the latter for short filaments is pointed out. The potentiometer method used in one pyrometer has considerable merit.

The Measurement of Heat Flow from Furnace Walls. C. B. Bradley. (American Society of Mechanical Engineers: Industrial Heating, 1945, vol. 12, Aug., pp. 1318–1320). Methods of measuring the flow of heat through a furnace wall are discussed and a device consisting of two thermocouples mounted in bakelite for fixing to slabs of insulating material is described; this is used to measure the insulating efficiency of the slab. Practical difficulties encountered with this method are pointed out.

HEAT-TREATMENT

(Continued from pp. 6 A–8 A)

The Application of Ms Points to Case Depth Measurement. E. S. Rowland and S. R. Lyle. (American Society for Metals, Oct., 1945, Preprint No. 24). A method of measuring case depth has been described previously by the authors (*see* Journ. I. and S. I., 1945, No. II., p. 111 A). In the present paper the results obtained when applying the method to a number of low-alloy chromium-nickel steels with carbon ranging from 0·40% to 1% are presented and discussed.

Time-Temperature Transformation Curves for Use in the Heat-Treatment of Cast Steel. C. T. Eddy, R. J. Marcotte and R. J. Smith. (American Institute of Mining and Metallurgical Engineers, Technical Publication No. 1846: Metals Technology, 1945, vol. 12, Sept.). An investigation is reported the objects of which were: (1) To determine the S-curves for a 0·30%-carbon steel and three low-alloy chromium-nickel steels; (2) to ascertain whether the published S-curves for wrought steels can be used for cast steels of similar composition; and (3) to prepare S-curves for a number of low-alloy cast steels. For the four steels referred to in (1) it was found that there were only very slight differences between the curves for the wrought and the cast steels of similar composition.

Time-Temperature Relations in Tempering Steel. J. H. Hollomon and L. D. Jaffe. (American Institute of Mining and Metallurgical Engineers, Technical Publication No. 1831: Metals Technology, 1945, vol. 12, Sept.). A study was made of the tempering of fully quenched steels differing only in carbon content, tempered over a wide range of time at temperatures from 65° F. to just below the critical point so as to establish a method of finding the combinations of temperature and time that produce the same hardness. The experimental details and the results obtained are given in Part I. and the method developed for the application of the results is described in Part II.

Coalescence of Cementite in the Products of the Decomposition of Austenite. H. Jolivet. (Revue de Métallurgie, Mémoires, 1943, vol. 40, Feb., pp 33–47; Mar., pp. 65–72). After discussing the principles on which the coalescence process in the solid solution is based, the author presents the results of his investigations and draws the following conclusions: The coalescence of cementite in the products of the decomposition of austenite takes place on heating the steel to below the Ac_1 point, and the finer the initial structure of the steel, the more rapid is the process; (2) the process of transformation is connected with the diffusion and dissolution of carbides; (3) the results of the heat-treatment can be estimated by microscopical examination, and the process corrected if necessary; (4) the determination of the size of the grains, by a method suggested by the author, considerably improved the results obtained.

Softening of Steel by the Isothermal Transformation of Austenite. F. F. Dodson. (Machine Shop Magazine, 1945, vol. 6, Nov., pp. 87–90). A comparison of ordinary annealing and isothermal annealing is presented. Each type of steel has its own optimum temperature for isothermal treatment, and to achieve the best results it is necessary to find the temperature at which the austenite begins to transform and the time taken for complete transformation. It is essential to allow sufficient time at the austenitizing temperature to bring the constituents to one homogeneous solid solution, and to control closely the temperature during the transformation period.

Heat-Treatment Study of Pearlitic Malleable Cast Iron. R. W. Lindsay and J. E. Atherton, jun. (American Foundryman, 1945, vol. 8, Sept., pp. 27–32). An investigation of the effects of two heat-treatments on the properties and microstructure of pearlitic malleable cast iron is reported. In the first, specimens were quenched in oil and tempered at subcritical temperatures for various lengths of time, and in the second, specimens were quenched to various subcritical temperatures at which they were held for different times. At a given tempering temperature

in the first treatment, the hardness of the martensitic structure decreased rapidly in the initial stages and then more gradually as the tempering time was lengthened. Isothermal transformation at from 1200° F. down to 1000° F. produced nodular pearlite which increased in fineness as the transformation temperature decreased. Isothermal transformation at below 1000° F. produced the acicular structure known as bainite.

Liquid Carburizing. J. O. Parker. (Australian Institute of Metals: Australasian Engineer, 1945, Oct., pp. 37–46). An account is given of the process of liquid-carburizing. The following aspects are discussed: Application and limitations of the process, selective carburizing, furnaces, containers, salts, bath control, nature of the process, and several methods of testing. The selection of suitable steels, recommended designs, effect of carbon content, case hardness and core toughness are also dealt with.

The Flame-Hardening of Different Qualities of Cast Iron. G. Kritzler and H. Killing. (Giesserei, 1942, vol. 29, Dec. 25, pp. 429–437). Several series of tests were made on bars 28 mm. in dia. of six qualities of cast iron to determine the effect of flame-hardening. The iron analyses ranged from 0·09% to 0·78% of combined carbon with 3·66% to 1·63% of silicon, and one contained 0·56% of molybdenum. A marked increase in the surface hardness of the ferritic cast iron was obtained by flame-hardening, and there was some increase in the core hardness on heating in a furnace and quenching which was not entirely accounted for by the heat-treatment alone. Chemical and metallographic examination showed that the matrix took up carbon from the graphite. A surface hardness as high as Brinell 550 was obtained with the pearlitic cast irons. All the hardened irons maintained their hardness on applying tempering treatments at 250–300° C. even after 200 hr. In the ferritic cast iron the combined carbon was increased from 0·09% to 1·03% by the furnace treatment, whereas with flame treatment for 25 sec. it increased to 0·7%.

Induction Hardening and Austenitizing Characteristics of Several Medium Carbon Steels. D. L. Martin and W. G. Van Note. (American Society for Metals, Oct., 1945, Preprint No. 17). The hardenability and transformation characteristics of a 0·50%-carbon steel, a 1·50%-manganese steel, a 3·50%-nickel steel, a chromium-nickel steel, and a manganese-silicon steel were studied to determine their suitability for induction-hardening. The steels with low Ac_1 and Ac_3 temperatures, little or no free ferrite, and medium to deep hardenability were ideal for induction-hardening.

Metallurgical Characteristics of Induction-Hardened Steel. J. W. Poynter. (American Society for Metals, Oct., 1945, Preprint No. 22). A comparison is made between the effects of induction-hardening and ordinary furnace-heating and quenching of bars of steel S.A.E. 4340 (a chromium-nickel-molybdenum steel). In the former case the depth of hardening is increased by increasing the heating time and reducing the power input, or by raising the surface temperature. The hardness depth is more easily controlled by the power input and time than by changes in the current frequency. What is often called "superhardness" in some induction-hardened steel seems to be related to the existence of internal stresses and is not caused by the induced currents.

Spark-Gap Converter as High-Frequency Power Source for Induction Heating. O. Weitmann. (Steel, 1945, vol. 117, Nov. 19, pp. 114, 130–132). The design of spark-gap converters and the circuits which have been developed for induction heating are discussed.

The Place of Radiant, Dielectric and Eddy-Current Heating in the Process Heating Field. L. J. C. Connell, O. W. Humphreys, and J. L. Rycroft. (Journal of the Institution of Electrical Engineers, 1945, vol. 92, Dec., pp. 464–465). Factors influencing the selection of one of the following methods of heating for a given industrial process are considered: (1) Conduction; (2) convection; (3) radiation; (4) dielectric heating; and (5) eddy-current heating.

Nitriding Engine Parts. W. Roth. (Steel, 1945, vol. 117, Nov. 19, pp. 123, 184–187). Plant and equipment for nitriding aero-engine cylinders, gears and crankshafts are described and illustrated.

A Mechanism of the Surface Decarburization of Steel. W. A. Pennington. (American Society for Metals, Oct., 1945, Preprint No. 30). A study was made of the decarburization of an ordinary carbon steel of eutectoid composition at temperatures in the 690–925° C. range. A mixture of hydrogen and water vapour was used to effect the decarburization. Micrographs are presented showing the progress of decarburization with time at the different temperatures. Distinct ferrite banding was found where the decarburization was carried out in the critical range (730–895° C.). There was banding below the lower critical point at 690° C., but it was not so distinct; there seemed to be no banding whatever at above the upper critical point. It is suggested that the carbon reaches the surface by diffusing in solid solution as either dissolved elementary carbon or iron carbide, regardless of whether the iron is in the austenitic or ferritic condition.

Preventing Surface Decarburization in Large Shaved Transmission Gears. E. G. de Coriolis. (Iron Age, 1945, vol. 156, Nov. 29, pp. 56–61). The methods and equipment used by a tank manufacturer for heat-treating large transmission gears after "shaving" are presented. The procedure described involves several innovations, notably the prevention of surface decarburization by the use of bell-type furnaces in which the gears are allowed to cool to less than 1000° F. before removal and subsequent hardening.

Heat-Treating Tank Parts in Buick Plant. (Industrial Heating, 1945, vol. 12, Aug., pp. 1292–1316). An illustrated description is given of a special heat-treating installation of the General Motors Corporation for the gas-carburizing, hardening, and tempering of parts for tank drives.

High-Speed Metal-Heating with Burners Radiant Ceramic. H. W. Smith, jun. (Engineering Materials and Processing Methods, 1945, vol. 22, Oct., pp. 1074–1078). A description is given of a ceramic gas burner for heat-treatment furnaces. The burner is cup-

shaped and recessed into the wall, and the design is such that the surface of the cup becomes incandescent so that the charge is heated by radiation.

Heat-Treatment. (Automobile Engineer, 1945, vol. 35, Nov., pp. 505–507). A description is given of a small vertical cylindrical forced-air-circulation furnace for heat-treating at temperatures up to about 700° C. It is equipped with two thermocouples recording the temperatures of the furnace and the charge on the same chart.

The Possibilities of Water-Quenching Certain Special Substitute Steels. G. Delbart and G. Wiltz. (Revue de Métallurgie, Mémoires, 1943, vol. 40, Nov., pp. 338–342). Tensile and impact specimens of chromium and chromium-vanadium steels, taken from 25-mm. billets, were subjected to water-quenching under different conditions, followed by tempering for 6 hr. at 650° C. The effect of quenching was observed, and tensile and impact tests were made as well as microscopical examination. It was found that slower or interrupted quenching seemed to be the best way to achieve a satisfactory hardening effect. The ageing symptoms were also investigated by means of Mesnager impact tests carried out after different treatments.

Quenching of Steel Balls and Rings. V. Paschkis. (American Society for Metals, Oct., 1945, Preprint No. 20). The temperature-time-volume relationships obtained when quenching steel spheres and cylindrical rings were investigated using the heat and mass flow analyser at Columbia University. General curves for spheres are presented which show the delaying effect of the heat of transformation in the 250–150° C. range. Data on the changes in the thermal conductivity and specific heat with temperature are also presented and discussed.

Production Cold-Treatment. A. J. T. Eyles. (Mechanical World, 1945, vol. 118, Nov. 16, pp. 543–545). The theory of the effect of cold-treatment in assisting the complete transformation of austenite to martensite in tool steels is explained, and procedures for treating various tools at −120° F. are given.

WELDING AND CUTTING

(Continued from p. 8 A)

Welding Mild Steel. H. O. Westendarp, jun. (Steel, 1945, vol. 117, Nov. 26, pp. 94–95, 123). Data are presented on the rates at which metal is deposited when welding mild steel at different current strengths using electrodes to the American Welding Society specifications, as well as on the properties of the welded joint obtained.

Brazing Alloy Tool Tips by Induction Heating. T. A. Vernor and E. F. Adams. (Steel Processing, 1945, vol. 31, Oct., pp. 652–653). An illustrated description is given of the equipment and process for utilizing induction heating for the brazing of tungsten-carbide tips to mild steel tools.

Aluminium Bonded to Steel or Cast Iron. M. G. Whitfield and V. Sheshunoff. (Engineering Materials and Processing Methods, 1945, vol. 22, Oct., pp. 1090–1096). Applications of the Al-Fin process of bonding aluminium to cast iron and steel are described with details of tests on the strength of the joint. The principal applications are fixing aluminium cooling fins on aero-engine cylinders, and making steel-backed aluminium bearings.

Modern Electric Weld Tube Mills. J. Lucas. (Iron and Steel Engineer, 1945, vol. 22, Oct., pp. 50–57). The development of machines for the continuous electric welding of strip into tubes of small and large diameter is described and illustrated.

Chemical Factors Affecting the Welding Properties of Stabilized 18-8 Stainless Steel. F. H. Page, jun. (Welding Journal, 1945, vol. 24, Oct., pp. 929–932). An investigation of the welding properties of 208 heats of stainless steel stabilized with titanium and 36 stabilized with columbium is reported. The results indicated that the cost of oxy-acetylene or atomic-hydrogen welding these steels may be materially decreased by slight changes in the chemical composition within the existing United States Army and Navy specifications.

The Spot Welding of NE 8715, NE 8630 and SAE 4340 in the 0·125-In. Thickness. W. F. Hess, W. D. Doty, and W. J. Childs (Welding Journal, 1945, vol. 24, Oct., pp. 521-S–530-S). This report describes work done for the War Production Board by the Rensselaer Polytechnic Institute in determining the optimum conditions for making tempered spot welds in three chromium-nickel-molybdenum steels. The tempering of the weld in the welding machine greatly improves the mechanical properties of the joint and makes it possible to spot-weld steels which are unweldable by conventional methods.

The Causes of Fissure Formation Tendency in Welded Chromium-Molybdenum Structural Steels. A. Antonioli. (Iron and Steel Institute, 1946, Translation Series, No. 261). This is an English translation of a paper which appeared in Stahl und Eisen, 1942, vol. 62, June 25, pp. 540–545 (*see* Journ. I. and S. I., 1943, No. I., p. 18 A).

Underwater Welding. J. R. Morrill. (Steel, 1945, vol. 117, Dec. 3, pp. 112–113, 153). Techniques for welding under water are described which were developed for the salvage of sunken vessels and repairing damaged ships, pipes and tanks.

Limitations in the X-Ray Testing of Welds. G. A. Homes and A. Portevin. (Revue de Métallurgie, Mémoires, 1943, vol. 40, Apr., pp. 97–107). Among the many factors which influence the X-ray testing of welds, the nature, size and location of defects are of great importance, and they form the subject discussed in this report. Artificially produced defects in welds are examined, and it is shown that certain internal defects cannot be detected by the X-rays alone; this method should be supplemented by

magnetic examination. This applies particularly to gas and slag inclusions the size of which is less than 5% of the thickness penetrated by the X-rays.

Removal and Repair of Steel Casting Defects. R. A. Pomfret. (American Foundryman, 1945, vol. 8, Sept., pp. 48–53). The techniques for cutting defective areas out of steel castings with the oxy-acetylene torch and of filling in with weld metal are described.

Some Developments in Oxy-Acetylene Applications. G. E. Bellew. (Iron and Steel Engineer, 1945, vol. 22, Oct., pp. 62–65). Applications of oxy-acetylene cutting in the steelworks are reviewed. These include deseaming billets, cutting risers from castings, and repairing ingot-stripper bits and tongs.

Recent Developments in Machine Flame Cutting. E. H. Witt. (Australian Welding Institute: Australasian Engineer, 1945, Oct., pp. 51–54). The present position of the machine flame-cutting process is outlined and different types of machines are described. Stack and heavy cutting, and the economic side of the process are dealt with.

MACHINING

(Continued from p. 9 A)

Milling Cast Iron with Carbide Cutters. (American Society of Mechanical Engineers: Machinery, 1945, vol. 67, Dec. 20, pp. 689–697). An extensive investigation is reported of the inter-relationship of tooth design, cutting speed, feed per tooth, type of cast iron, tool life, power required, and cost when milling cast iron with carbide-tipped cutters.

The Use of Carbide Tools. J. Jaquet. (Revue de Métallurgie, Mémoires, 1943, vol. 40, Aug., pp. 225–231). Rational methods and practical hints for the utilization of carbide tools are given, and the factors contributing to a higher production efficiency in comparison with high-speed steel tools are discussed.

Nomographs for Analysis of Metal-Cutting Processes. M. E. Merchant and N. Zlatin. (Mechanical Engineering, 1945, vol. 67, Nov., pp. 737–742). In this paper a number of charts and nomographs dealing with variables such as coefficient of friction, shear stress, frictional force, shear velocity, and cutting ratio, are presented for analysing all orthogonal cutting processes wherein a continuous chip is produced. (An orthogonal cutting process is one wherein the tool has a single straight cutting edge perpendicular to the direction of the tool motion relative to the work).

Detection, Causes and Prevention of Injury in Ground Surfaces. L. P. Tarasov. (American Society for Metals, Oct., 1945, Preprint No. 26). Information on injury to ground metal surfaces which is widely scattered in the literature is reviewed and supplemented by the author's work on stresses in ground surfaces. The subject is dealt with in the following order: (1) Methods of detecting cracks, stresses and burns in ground surfaces; (2) cracks and crack patterns, including those occurring spontaneously during or after grinding and cracks revealed by etching; (3) metallurgical factors which have repeatedly been shown to cause hardened steels to be sensitive to cracking during grinding; (4) decreasing this sensitivity by improving the heat-treatment; (5) the extent to which surface cracks may be injurious having regard to the subsequent application of the ground part; and (6) methods by which stresses can be eliminated from surfaces after final grinding.

PROPERTIES AND TESTS

(Continued from pp. 11 A–14 A)

Cast Iron as a Material. E. Piwowarsky. (Giesserei, 1943, vol. 30, June, pp. 141–152). The properties of cast iron and its development as a constructional material are reviewed. Qualities of cast iron have been developed which can be rolled, forged, and pressure-die-cast. The Nipper rolling process for cast iron is referred to and brief details are given of a method of reinforcing iron castings with a very low carbon steel containing from 1% to 3% of silicon according to the thickness of the casting.

The Degree of Saturation and the Tensile Strength of Cast Iron. F. Bischof. (Giesserei, 1942, vol. 29, Dec. 25, pp. 437–439). The literature on formulæ for the degree of carbon saturation in cast iron and for the relation between the tensile strength and the saturation is reviewed, and difficulties in the determination of the tensile strength from the composition are discussed.

Gray Cast Iron. T. E. Barlow and C. H. Lorig. (American Foundryman, 1945, vol. 8, Sept., pp. 57–63). The relationships between the tensile strength, Brinell hardness and composition of grey cast iron are discussed.

Some Problems of the Metallic State. Sir Lawrence Bragg. (North-East Coast Institution of Engineers and Shipbuilders: Iron and Steel, 1945, vol. 18, Nov. 30, pp. 531–535). *See* p. 12 A.

Complex Properties in Metallurgy. A. Portevin. (Revue de Métallurgie, Mémoires, 1943, vol. 40, June, pp. 161–174). In addition to properties normally defined by scientific standard methods, there exist many other characteristic features of metals, such as, for example, flowability, forgeability, machinability, weldability, hardenability, corrodibility, etc., upon which the successful application of the metal depends. Taking into consideration the interdependence of these properties, which complicates production prob-

lems, the author stresses the necessity of examining them and recommends methods of testing.

Fracture of Metals Under Combined Stresses. D. J. McAdam, jun. (American Society for Metals, Oct., 1945, Preprint No. 29). The manner in which combined stresses contribute to brittle fracture is discussed. For a specific temperature, rate of deformation, and amount of previous plastic deformation, the resistance of a metal to fracture (the technical cohesive strength) may be represented by a curved surface in a diagram with the three principal stresses as co-ordinates. From two-dimensional diagrams based on the experiments of several investigators, three-dimensional diagrams have been derived to represent the technical cohesive strength of brittle and ductile metals.

The Fracture Stress of Steel. C. Zener. (Reviews of Modern Physics, 1945, vol. 17, Jan., pp. 20–26). A review of the results of research work at Watertown Arsenal on the fracture stress of steels is presented. The fracture-stress curve is that curve which gives for each strain the stress at which the material would fracture if further plastic deformation could be prevented; this curve and the flow-stress curve are discussed. If the fracture stress is to be controlled, the size of the microcracks within the steel must be controlled. The microcracks are in some way related to the interfaces between the various phases. The rôle of physicists in such investigations is considered.

The Theory of Strain and the Fracture of Solids with Special Reference to Deformation in Iron. A. Eichinger. (Archiv für das Eisenhüttenwesen, 1944, vol. 18, Sept.-Oct., pp. 73–88). The process of slip in metals is irreversible. As long as the intermediate conditions exist the rigid values applicable to the equilibria can be used only in a hypothetical sense. Because of the many ways in which the final condition is affected by the previous history, new factors (*e.g.*, energy and impulse distribution, laminar and turbulent flow) must be sought, and these can only be found by a deeper study of the constitution of matter. The conditions influencing the deformation of iron are critically examined and discussed.

The Notched-Bar Impact Strength of Cast Steel at Low Temperatures. H. Juretzek and W. Trommer. (Giesserei, 1943, vol. 30, Jan. 22, pp. 21–24). The value of the impact test as a criterion of the behaviour of low-alloy cast steels at temperatures down to −180° C. is discussed and the literature is reviewed. The results of impact tests at +20°, −80°, and −180° C. on steels alloyed with combinations of three of the following elements: Nickel, manganese, aluminium, chromium, silicon and vanadium, are presented.

Effects of Cold-Rolling on the True Stress-Strain Properties of a Low-Carbon Steel. F. J. Mehringer and C. W. MacGregor. (American Institute of Mining and Metallurgical Engineers, Technical Publication No. 1849: Metals Technology, 1945, vol. 12, Sept.). The effects of cold-rolling on the true stress-strain properties of a low-carbon steel were investigated for total reductions up to 95%. Tension tests were made on the material after nearly complete ageing had taken place. The influence of heterogeneity and of the orientation of the specimen relative to the rolling direction were studied. The magnitude of the strain-ageing was also determined using true stress-strain relationships.

Stress Comparisons by Correlations with High Frequency Magnetic and Eddy Current Losses. P. E. Cavanagh. (American Society for Metals, Oct., 1945, Preprint No. 3). The possibility of using a high-frequency oscillator, the output of which is governed by magnetic and eddy-current losses, to make practical comparisons of stresses in metals is examined. Preliminary experiments are described which establish the fact that there is a correlation between high-frequency core losses and internal stresses. Examples are cited of the application of this method of testing to determine the optimum time of shot-peening required to produce compressive stresses at the surface of bars subjected to fatigue, and for predicting fatigue failures.

Relationships between the Deep-Drawing Properties of Autobody Sheet, Its Austenitic Grain Size and McQuaid-Ehn Carburizing Characteristics. K. J. B. Wolfe. (American Society for Metals, Oct., 1945, Preprint No. 27). An investigation of the causes of splitting during the intermediate forming operation in deep-drawing steel sheets is reported. Carburizing tests were carried out on samples from two batches, one giving consistently good results and the other consistently bad results in forming operations. The samples in the former case had fine austenite grains, whereas in the latter case they were coarse. The theory is advanced that this grain size depends on the distribution of carbide particles in the sheets and consequently on the carbide segregation in the ingot stage.

The Flowability of Metals and Alloys. P. Bastien. (Revue de Métallurgie, Mémoires, 1943, vol. 40, Dec. pp. 353–367). After discussing the laws of flowability of pure metals and alloys of binary and ternary systems the author gives the results of his experiments with a 0·25%-carbon open-hearth steel. The influence of temperature and of aluminium and silicon additions on the flowability of steel is described. The flowability is closely related to viscosity and superficial tension, and the testing of flowability, apart from being very useful in foundry practice, may serve as a helpful means of determining the solidification diagram for a given alloy.

Photo-Grid Techniques for Measuring Distortion. (Iron Age, 1945, vol. 156, Nov. 8, pp. 78–81). A technique, developed by an American corporation manufacturing aeroplanes, for producing grids on metal specimens is described. The grids are used for measuring distortion in tensile, punching, and drawing tests. Grids with 10 or 100 lines/in. can be produced.

Secondary Mechanical Properties. Internal Friction, Viscous Relaxation, Reactivity, Poisson's Ratio. P. Chevenard. (Revue de Métallurgie, Mémoires, 1943, vol. 40, Oct., pp. 289–300). The theory of resistance is based on the assumption that metals remain perfectly elastic below the limit of elasticity. The study of secondary mechanical properties, presented by the author, forms a valuable contribution to the recent research work which seeks to determine to what extent metals differ from a

perfectly elastic solid. The most sensitive parameter which defines this difference is the value of internal friction, measured by the Coulomb micro-pendulum. Poisson's ratio serves the same purpose. The Coulomb micro-pendulum and apparatus for measuring the Poisson's ratio are described in detail.

An Investigation of Different Qualities of Malleable Cast Iron with Reference to Their Torsional Fatigue Strength in the Smooth and Notched State, and Their Damping Capacity. J. Geiger. (Giesserei, 1943, vol. 30, Mar. 19, pp. 85–92). An earlier investigation of the damping capacity of cast iron (*see* Journ. I. and S. I., 1940, No. I., p. 205 A) has been extended to cover malleable cast iron. The results of damping measurements and torsional fatigue tests on three qualities of malleable cast iron using smooth, drilled and notched specimens are reported and discussed. The damping capacity was much higher than that of steel and the torsional fatigue strength was also higher. As the iron has good casting properties and is hardenable it is recommended for making aero-engine crankshafts, and tests on full-size crankshafts instead of on small specimens should be carried out.

Factors Affecting the Hardenability of Boron-Treated Steels. R. A. Grange and T. M. Garvey. (American Society for Metals, Oct., 1945, Preprint No. 10). The hardenabilities of four series of carbon steels (containing 0·40%, 0·52%, 0·63%, and 0·75% of carbon respectively), to each of which measured amounts of boron were added, are compared. The increase in hardenability due to boron is correlated with the boron content determined by a chemical method and with the amount of a characteristic constituent which appears in boron-treated steels after special heat-treatment. The increase in hardenability which results from the addition of the optimum amount of boron decreases with increasing carbon content; the inference is that boron will not increase the hardenability of hypereutectoid steel.

Determination of Most Efficient Alloy Combinations for Hardenability. H. E. Hostetter. (American Institute of Mining and Metallurgical Engineers, Technical Publication No. 1905: Metals Technology, 1945, vol. 12, Sept.). Hardenability increment factors for chromium, nickel, and molybdenum are presented. These take into account the relative costs of these three elements when added to steel and the changes in the Grossmann "ideal critical diameter" of bar (*i.e.*, the size that will just harden to a 50%-martensite structure at the centre when given the fastest possible quench) with different additions. An explanation, with examples, is then given of a method of using the increment factors to determine the most economical composition which will result in a given hardenability.

Relationship between Hardenability and Percentage of Martensite in Some Low Alloy Steels. J. M. Hodge and M. A. Orehoski. (American Institute of Mining and Metallurgical Engineers, Technical Publication No. 1800: Metals Technology, 1945, vol. 12, Sept.). The relationships between hardenability based on a 50%-martensite microstructure and hardenability on the basis of higher proportions of martensite have been studied by means of a metallographic survey of specimens subjected to the end-quench hardenability test. The results are presented by graphs which: (*a*) Correlate the hardenability on the 50% martensite basis with the hardenabilities on the basis of 99·5%, 95%, 90%, and 80% martensite structures; (*b*) correlate the calculated and actual hardenabilities on the basis of 99·9%, 95%, 90%, and 80% martensite structures; and (*c*) correlate the carbon content and the hardness of 99·9%, 95%, 90%, 80%, and 50% martensite structures.

The Influence of Titanium on the Hardenability of Steel. G. F. Comstock. (American Institute of Mining and Metallurgical Engineers, Technical Publication No. 1904: Metals Technology, 1945, vol. 12, Sept.). The effect of titanium on the hardenability of steel depends on the heat-treatment, on whether the total titanium or the acid-soluble titanium is used as the basis for the calculations, and on the titanium/carbon ratio. Additions of up to 0·1% of titanium increase the hardenability effectively, but with amounts increasing above 0·2% the hardenability decreases. The hardenability factor for titanium may be based on the acid-soluble quantity present provided that account is taken of the fact that the insoluble titanium decreases the hardenability by rendering ineffective a proportional amount of carbon.

Microhardness Testing of Materials. V. E. Lysaght. (Engineering Materials and Processing Methods, 1945, vol. 22, Oct., pp. 1079–1084). Applications of the Knoop indenter are described. In particular, details are given of the Tukon instrument with which Knoop hardness numbers under loads in the range of 25 to 3600 g. can be obtained.

Hardness of Metals and Alloys. Its Measurement. L. Guillet. (Revue de Métallurgie, Mémoires, 1943, vol. 40, Sept., pp. 266–275). Hardness-testing methods, based on the principle of resistance against scratching and penetration, and of rebound after shock, are reviewed. Some theoretical explanations of hardness are also given. The hardness of metals seems to be connected with their atomic volume—the softer the metal, the greater its atomic volume. The value of hardness is considerably influenced by transformations which occur in solid solutions, such as precipitation, and also by diffusion, cold-work and recrystallization.

Ageing Phenomena in Cast Iron. E. Piwowarsky. (Giesserei, 1942, vol. 29, Oct. 16, p. 358). The ageing tendency of specimens from a special cast iron containing 3·6% of carbon, 2·6% of silicon and 0·75% of phosphorus was examined. They were heated for 20 min. at temperatures in the 250–550° C. range and quenched in water. Hardness determinations were made immediately and after intervals of 20, 40, 120 and 160 hr. The hardness of the specimens tested immediately after quenching increased markedly when the temperature of the treatment was increased from 350° to 450° C. After only 40 hr. a marked increase in hardness was noted, the maximum increase occurring after 160 hr.

A Method of Assessing Wear Due to Friction and Corrosion. P. M. Fisk. (Sheet Metal Industries, 1945, vol. 22, Dec., pp. 2138–2141, 2146). A description is given of a machine which was specially

made to study the wear and corrosion of hinges for doors and windows, and some results obtained with it are discussed.

Recent Studies on Metallic Wear By Sliding Friction. L. Decroix. (Revue de Métallurgie, Mémoires, 1943, vol. 40, Feb., pp. 48–57; Mar., pp. 73–84; Apr., pp. 114–122). The author presents a comprehensive review of recent research work on metallic wear by friction, and reports the results of his own investigations. The amount of wear depends primarily on the hardness and strength of the metal. Its mechanical properties are affected by the heat generated by friction, and the behaviour of the metal at high temperatures should be considered when the resistance to wear is tested. The process of friction causes chemical transformations in the worn layer by continuous reactions between gas, liquid and metal.

A Survey of the Theory of Ferromagnetism. J. H. Van Vleck. (Reviews of Modern Physics, 1945, vol. 17, Jan., pp. 27–47). There is similarity in many respects between the theory of ferromagnetism and the theory of valence. Both topics are readily tractable only for models corresponding to the limiting cases in which the electrons are treated respectively as tightly bound on individual atoms and as wandering freely from atom to atom without cognizance of each others' positions.

Effect of Small Stresses on Magnetic Properties. R. M. Bozorth and H. J. Williams. (Reviews of Modern Physics, 1945, vol. 17, Jan., pp. 72–80). Measurements were made of the changes of magnetization that occur in steel when very small stresses are applied and removed. Curves showing the changes in the magnetic properties are presented and discussed.

Mass Temperature Effects on Quenching 36 Per Cent. Cobalt Magnet Steel. B. Falk. (American Society for Metals, Oct., 1945, Preprint No. 6). The effect of mass on the magnetic properties of a 36%-cobalt steel are discussed and experiments are described the object of which was to determine the heat-treatments for this steel which would produce the optimum magnetic properties in the different commercial sizes. There is a different critical quenching temperature for different masses of the same steel which produces the maximum $BH_{max.}$ and this temperature (in Fahrenheit) could be found by the equation $T = 1605 + (912/F)$, where F is the ratio of surface area to volume.

Multi-Specimen Testing Equipment for Long-Time Creep Tests. A. Thum and K. Richard. (Iron and Steel Institute, 1946, Translation Series, No. 262). This is an English translation of a paper which appeared in Archiv für das Eisenhüttenwesen, 1943, vol. 17, July-Aug., pp. 29–33 (*see* Journ. I. and S. I., 1944, No. II., p. 133 A).

Investigation of a Type of Failure of 18-8 Stabilized Stainless Steel. W. Kahn, H. Oster and R. Wachtell. (American Society for Metals, Oct., 1945, Preprint No. 15). A report on an investigation of the failure of aero-engine exhaust manifolds of 18/8 stabilized stainless steel is presented. A type of failure was traced which was due to more carbon being precipitated in the steel than the stabilizing element could absorb.

Graphite in Cold-Rolled Subcritically Annealed Hypoeutectoid Steels. M. A. Hughes and J. G. Cutton. (American Society for Metals, Oct., 1945, Preprint No. 13). A study was made to determine the effect of (*a*) temperature, (*b*) residual alloying element, (*c*) cold-reduction, (*d*) mode of deoxidation, (*e*) full annealing before cold-reduction, and (*f*) carbon content, on the susceptibility of hypo-eutectoid steels to graphitization when cold-rolled and annealed at subcritical temperatures. Fine-grained steel strip with carbon in the 0·08–0·67% range was graphitized when cold-rolled and subcritically annealed. Hot-rolled silicon-manganese steel strip was also graphitized by this treatment. Data on the rate of solution of graphite in cold-rolled annealed strip at normal heat-treatment temperatures are presented.

Residual Elements and Gas Contents of Cast Iron. J. E. Hurst. (Staffordshire Iron and Steel Institute: Metallurgia, 1945, vol. 33, Nov., pp. 9–12: Foundry Trade Journal, 1945, vol. 77, Dec. 27, pp. 363–369). Examples are described of the marked effect which traces of residual elements or of gas in cast iron can have upon its physical properties. The examples relate to a high-silicon heat-resisting iron, an austenitic nickel cast-iron and a manganese iron for marine diesel-engine cylinders.

Gas Evolution from Cast Steel at Room Temperature. H. H. Johnson, L. H. Arner and H. A. Schwartz. (American Society for Metals, Oct., 1945, Preprint No. 14). The composition and rate of evolution of gas from freshly cast steel at or near room temperature was studied. The gases consisted mainly of carbon monoxide, nitrogen and hydrogen. The amount of the first two of these gases evolved from unit weight of electric-furnace medium-manganese steels differed very little from steel to steel, but the amount of hydrogen varied greatly.

Contribution to a Study of the Mechanical Properties of Special Substitute Steels in Relation to the Section of Thermally Treated Pieces. G. Delbart. (Revue de Métallurgie, Mémoires, 1943, vol. 40, Nov., pp. 321–337). The author presents the results of mechanical tests on the manganese, manganese-vanadium, manganese-chromium, and manganese-chromium-vanadium steels used as substitutes for high-alloy nickel-chromium steels. Test-pieces were taken in both longitudinal and transverse directions from billets of various dimensions (200, 100, 50 and 25 mm.) after heat-treatment. The study of the mechanical properties was supplemented by microscopical examination. An appropriate heat-treatment is suggested for each of the steels examined to obtain satisfactory results in pieces of large dimensions. It is also pointed out that a less homogeneous sorbitic structure, containing free ferrite after heat-treatment, may in certain cases improve their damping capacity.

Effect of Variations in Composition and Heat-Treatment on Some Properties of 4 to 6 Per Cent. Chromium Steel Containing Molybdenum and Titanium. G. F. Comstock. (American Society for Metals, Oct., 1945, PreprintNo. 4). With titanium/carbon ratios of between 3·5 and 5·5 in 5%-chromium/molybdenum/titanium steels, much better notched-bar impact strengths and high-temperature rupture strengths

are obtained than with higher titanium. About 1% of silicon in these steels gives superior resistance to oxidation and does not reduce the impact and high-temperature strengths if the manganese content is 0·75–1·00% and the steel is tempered at about 730° C. without annealing or normalizing.

Iron-Manganese Alloys. R. S. Dean, J. R. Long, T. R. Graham and R. G. Feustel. (American Society for Metals, Oct., 1945, Preprint No. 5). The effect of increasing amounts of manganese in the 1–7% range on the properties of cold-rolled steels was investigated. In the soft condition the tensile strength is increased by about 11,000 lb./sq. in. for each 1% of manganese. The elongation drops rapidly at first (by 5% for each 1% of manganese) and then more slowly at 7% manganese. Cold-working to 80% reduction in thickness increases the tensile strength to 192,600 lb./sq. in.; it produces an elongation of 2·7% on 2 in. and a hardness of Rockwell C 38. The effects of different heat-treatments are also discussed.

Effect of Nickel on Physical Properties and Thermal Characteristics of Some Cast Chromium-Molybdenum Steels. N. A. Ziegler and W. L. Meinhart. (American Society for Metals, Oct., 1945, Preprint No. 28). The effect of additions of up to 2% of nickel on the thermal and physical properties of steels containing 2·5–9·0% of chromium and 0·5–1·5% of molybdenum was investigated. The nickel improved the strength in all cases, without undue reduction of ductility and impact resistance. The effect was more pronounced with the 2·5–5·0% chromium steels than when the chromium content was 7–9%. The hardness developed on welding low-carbon nickel steels was less than that in high-carbon nickel-free steels of the same strength.

The Properties of Cast Manganese Steel and the Effect of Manganese on Cast Iron. F. Bischof. (Giesserei, 1942, vol. 29, Nov. 13, pp. 381–387). The properties of cast manganese steel, in particular steel with 10–12% of manganese, and the effects of manganese on the properties of cast iron were studied, special attention being given to contraction, expansion, thermal conductivity, wear-resistance, and work-hardening.

Stainless Steels for Turbine Blading. J. H. G. Monypenny. (Transactions of the Institute of Marine Engineers, 1945, vol. 57, Dec., pp. 129–140). *See* p. 14 A.

Selecting the Proper Heat-Resistant Steel. R. A. Lincoln. (Iron Age, 1945, vol. 156, Nov. 8, pp. 74–77). Data on the scaling-resistance and mechanical properties of the chromium-nickel heat-resisting steels are presented and discussed.

Ball Wear in Wet Grinding Mills. N. A. MacLeod. (American Institute of Mining and Metallurgical Engineers, Technical Publication No. 1918: Metals Technology, 1945, vol. 9, Nov.). Grinding tests were made in a small ball mill 10½ in. in dia. × 9 in. long, rotated at 72 r.p.m. Chill-cast, sand-cast and annealed steel balls were used to grind different types of ore and the wear was determined by the loss in weight. Siliceous ores and ores rich in pyrites caused a high rate of wear in wet-grinding, whilst the presence of kaolinitic material reduced the rate of wear. The grindability index of an ore is not necessarily an expression of its effect on ball consumption.

Selection of Die Steels for Cold Work. W. H. Wills. (Iron Age, 1945, vol. 156, Nov. 22, pp. 58–61). The structure and physical properties of the following four groups of die steels used for cold-work are described: (1) Water-hardening (carbon and carbon-vanadium) steels; (2) manganese and other low-alloy oil-hardening steels; (3) high-carbon high-chromium steels; and (4) air-hardening steels. Factors affecting their selection for special duties are discussed.

Electronic Measurement, Analysis and Inspection. (Machinery, 1945, vol. 67, Dec. 27, pp. 729–732). Industrial applications in which electronic devices are used for counting and detecting hidden defects, and controlling temperatures are described.

British *En* Alloy Specification. J. H. G. Monypenny. (Iron Age, 1945, vol. 156, Nov. 15, pp. 71–76). The British emergency specifications for steel are described and presented in the form of tables. The specifications were based on the physical and mechanical properties rather than on the chemical analysis.

METALLOGRAPHY AND CONSTITUTION

(Continued from p. 15 A)

Anti-Reflection Films for Metallographic Objectives. J. R. Benford. (American Society for Metals, Oct., 1945, Preprint No. 1). Experimental studies on improvements in the performance of metallographic microscopes due to anti-reflection films on the surface of the objective lens show that the improvement depends on the design of the objective and on the type of specimen. The improvements accomplished by the filming consist of a better image contrast and a shorter photographic exposure. Micrographs are submitted showing comparative performance between filmed and unfilmed objectives.

Electron Microscopic Investigations of Surface Structure. R. D. Heidenreich. (S.A.E. Journal, 1945, vol. 53, Oct., pp. 588–594). Examples of the condition of metal surfaces as revealed by the electron microscope are presented and discussed. The depth of focus of the electron microscope is of the order of 10 times that of the light microscope, so that structures with variations in elevation as great as several microns will yield micrographs that are uniformly in focus.

Defects in Steel and Their Detection. A. J. K. Honeyman and A. Fisher. (Journal of the West of Scotland Iron and Steel Institute, 1945, vol. 52, Part III., pp. 39–57). A brief account of defects in steel and methods of detecting them is given and illustrated by 38 figures and micrographs. Surface examination,

the deep-etch test, and the sulphur-print test are described. These reveal: (1) Pipe or axial segregation; (2) other types of ingot segregation; (3) reeds; (4) rokes; (5) shell; (6) overlaps; and (7) fishtail. Examples of each of these are described. Crack-detection tests are also described.

Detection of Deep Flaws in Metals by Supersonic Wave. D. O. Sproule. (Machinist, 1945, vol. 89, Dec. 8, pp. 2013–2016). A description is given of an instrument for transmitting supersonic waves through metal and receiving echoes from flaws within the metal. It is claimed that a $\frac{1}{32}$-in. dia. hole 4 ft. below the explored surface can easily be detected.

A Method of Revealing the Microstructure of Nickel Deposits on Steel. R. Stokes. (Metallurgia, 1945, vol. 33, Nov., pp. 21–22). A procedure for etching nickel deposits on steel which etched the nickel deeply with only slight attack on the steel and the interface is described.

Radiography and Shipyard Welding. R. Halmshaw. (Welding, 1945, vol. 13, Nov., pp. 451–455, 461). The principles of gamma-radiography are explained and a typical radon source 1 mm. in dia. $\times$ 2 mm. long in a glass bulb in a lead or tungsten-steel container is described. Some radiographs of shipyard welds are reproduced and discussed.

The Advantages and Limitations of Gamma-Ray Radiography on Small Steel Castings. R. H. Frank. (American Foundryman, 1945, vol. 8, Oct., pp. 50–61). A general and well-illustrated review of gamma-ray radiography as an inspection instrument and as a method of testing castings is given.

X-Ray Standards for Purchasing Castings. L. W. Ball. (Iron Age, 1945, vol. 156, Nov. 22, pp. 62–64). A difficulty in drawing up acceptance specifications for castings is the unpredictability of internal discontinuities and the limited degree to which test-bars represent the quality of the corresponding cast parts. For the acceptance of castings, agreement can be furthered by examining radiographs and interpreting heterogeneity, if present, according to the importance of the area in which it is located.

Influence of Carbon Content upon the Transformation in 3 Per Cent. Chromium Steel. T. Lyman and A. R. Troiano. (American Society for Metals, Oct., 1945, Preprint No. 16). The effects of time and temperature on the transformations in seven 3%-chromium steels with carbon in the 0·08–1·28% range were investigated with the microscope, the dilatometer and by X-ray diffraction. Isothermal transformation diagrams for these steels are presented.

Transformation of Austenite in a Steel Containing 3 Per Cent. Chromium and 1 Per Cent. Carbon. E. P. Klier. (American Institute of Mining and Metallurgical Engineers, Technical Publication No. 1855: Metals Technology, 1945, vol. 12, Sept.). An analysis was made of the transformation characteristics of a 1%-carbon, 3%-chromium steel by X-ray and metallographic methods. From the results obtained it is concluded that the bainite reaction in this steel is more complicated than previously reported by the author and T. Lyman for the low-carbon low-alloy steels.

Partition of Molybdenum in Hypereutectoid Iron-Carbon-Molybdenum Alloys. F. E. Bowman. (American Society for Metals, Oct., 1945, Preprint No. 2). The study of the partition of molybdenum between the ferrite and carbide resulting from the isothermal transformation of austenite as well as from tempering martensite is extended to hypo-eutectoid alloys of iron, carbon, and molybdenum. In these alloys the high concentration of molybdenum in the carbides formed isothermally at subcritical temperatures proves that molybdenum must diffuse during the eutectoid reaction. This diffusion of the molybdenum and the formation of the complex carbide $(Fe,Mo)_{23}C_6$ in alloys containing more than 0·50% of molybdenum provide an explanation for the retardation in the eutectoid reaction.

Critical Points of S.A.E. 4340 Steel as Determined by the Dilatometric Method. D. Niconoff. (American Society for Metals, Oct., 1945, Preprint No. 19). A dilatometer was employed to determine the critical points on heating a chromium-nickel-molybdenum steel. The position of the points depended upon the initial structure and the heating rate. The critical points on cooling depended on the time and temperature of soaking before cooling.

Isothermal Transformation of Austenite in One Per Cent. Carbon, High-Chromium Steels. T. Lyman and A. R. Troiano. (American Institute of Mining and Metallurgical Engineers, Technical Publication No. 1801: Metals Technology, 1945, vol. 12, Sept.). Microscopical, X-ray and dilatometric methods have been employed in determining the isothermal transformation diagrams for four steels containing 1% of carbon with 3%, 4%, 6%, and 9% of chromium respectively.

Temper Brittleness of Steels. H. Jolivet and R. Chouteau. (Revue de Métallurgie, Mémoires, 1943, vol. 40, Jan., pp. 14–24). Slow cooling after tempering of certain steels produces temper brittleness, which manifests itself by a difference between the impact values obtained after rapid and slow cooling. There are two theories which endeavour to explain this: (1) The theory of precipitation of one phase in the austenitic zone, and (2) the theory of decomposition of carbides. The results of the investigations, presented by the authors lead to the conclusion that both theories remain hypothetical, as it was impossible with the microscope to produce evidence of the precipitation or decomposition of the carbides.

What Can Be Deduced from a Solidification Diagram? J. Luneau. (Revue de Métallurgie, Mémoires, 1942, vol. 39, July, pp. 218–223). The binary solidification diagram is discussed with particular reference to the three following problems: (1) The distribution of alloying elements between the liquid and solid phases at a given temperature; (2) the proportion in which both constituents participate in the solution when the temperature changes and the liquid phase passes into the solid phase; and (3) the graphical determination of the mass passing from the liquid to the solid phase when the temperature decreases.

CORROSION OF IRON AND STEEL

(Continued from p. 16 A)

Some Principles of Corrosion of Metals and Alloys. G. Chaudron. (Revue de Métallurgie, Mémoires, 1943, vol. 40, July, pp. 193–201). The symptoms of superficial and internal, or intergranular, corrosion are discussed in detail: The corrosion depends on a great many factors, which are divided by the author into four main groups: (1) The attacking reagent; (2) the metal or alloy examined; (3) the conditions of work; and (4) the duration of the corroding process.

Passivity of Metals. P. Lacombe. (Revue de Métallurgie, Mémoires, 1943, vol. 40, Sept., pp. 257–265). The author suggests the following definition of passivity: A metal is said to be passive when, during a chemical or electrochemical transformation, it loses a great deal of its power to emit ions, this emission being suppressed by interposition of a gaseous, solid or even liquid film. Various methods of producing and destroying passivity, and the factors on which it depends, are discussed. The existence of a film is the condition necessary for conferring passivity on a metal, but it is only effective when the film is very thin, continuous and adhesive, and of an amorphous structure.

Oxide-Metal Layers Formed on Commercial Iron-Silicon Alloys Exposed to High Temperatures. R. Ward. (American Institute of Mining and Metallurgical Engineers, Technical Publication No. 1832: Metals Technology, 1945, vol. 12, Aug.). Structures of iron-silicon alloys containing from 0·70% to 5·8% of silicon were oxidized in air and in closed containers containing ferric oxide and mixtures of ferric oxide, iron powder and water at temperatures from 600° to 1200° C. The conclusions reached were: (1) At below 800° C. the diffusion of oxygen in alloys with less than 1·56% of silicon takes place preferentially along the grain boundaries; (2) at below 800° C. the diffusion in alloys with more than 2·55% of silicon appears to proceed by lattice diffusion; (3) when low-silicon alloys are oxidized at above 800° C. a layer of oxide particles is precipitated and this layer increases in depth with temperature and time; (4) with alloys containing more than 2·55% of silicon the character of the oxidation changes at 800° C. from a "pearlite" type to a structure similar to "Liesegang bands," and at above 1000° C. this in turn changes to a globular structure; (5) the Liesegang structure frequently comes off by spalling, whereas the pearlite scale is very often adherent; and (6) the character of the surface layers depends on the composition, temperature, rate of oxygen delivery, and, to a limited extent, time. Several micrographs of sections through the surface layers at 600 diameters are reproduced.

The Corrosive Action of Benzole Absorption Oils. C. M. Cawley and H. E. Newall. (Journal of the Society of Chemical Industry, 1945, vol. 64, Oct., pp. 285–290). This paper deals only with the corrosion which occurs in the stripping plant in the benzole absorption process. An account is given of a laboratory investigation with the object of determining the nature and origin of the substances causing corrosion. The main cause was found to be the action of ammonium thiocyanate formed by the reaction between ammonia and carbon disulphide in solution in the wash oil. The deposits of Prussian blue often found in benzole absorption plants are apparently formed by the reaction between ammonium thiocyanate and iron.

ANALYSIS

The Spectrographic Analysis of Austenitic Nickel-Chrome Steel. S. D. Steele and J. M. Johnston. (Journal of the Society of Chemical Industry, 1945, vol. 64, Oct., pp. 278–283). The object of the work recorded was to determine whether the range of spectrographic determinations could be extended to justify inclusion of both chromium and nickel in the spectro-analytical examination of steels. A satisfactory technique is described in detail whereby, from the viewpoint of production control analysis, determinations of chromium, nickel, silicon, manganese and aluminium can be made in chromium-nickel steels of the 18/8 type. The method incorporates the use of the flat-surface technique with a copper counter electrode. Plate calibration is obtained by the use of a rotating stepped sector wheel, the calibration curve being drawn by plotting densitometer readings against the logarithm of the relative intensities. The gap-width setting can be made within the permissible tolerance by the use of a feeler gauge. Assuming that the errors inherent in the method follow a symmetrical distribution, the accuracy which may be expected for determinations of chromium and nickel within the ranges 18% to 24% of chromium and 7% to 10% of nickel are $\pm 0{\cdot}47\%$ and $\pm 0{\cdot}20\%$ respectively.

The Occurrence of Calcium in Iron. (Bradley's Magazine, 1945, Dec., p. 7). A spectrographic technique for determining calcium in iron is described. From tests made on a number of irons it seems that all irons contain a small amount of calcium, the maximum range found being 0·005–0·010%. Large additions of calcium by means of calcium silicide to grey iron did not increase the calcium content of the final metal, which remained at 0·006%.

Modern Methods for the Quantitative Spectrochemical Analysis of Metal Alloys. R. Castro. (Revue de Métallurgie, Mémoires, 1942, vol. 39, Feb., pp. 54–60; Mar., pp. 84–96; Apr., pp. 112–122). A survey is presented of the spectrographic methods of analysing alloys with special reference to quantitative analysis. The author deals in separate sections

with the choice of rays, the analytical and photoelectric methods based on the measurement of differences in line intensity, the spectrochemical analysis of alloys in solution, and the elements detectable by spectrographic methods.

Modern Apparatus for Spectrochemical Qualitative and Quantitative Analysis of Alloys. R. Girschig. (Revue de Métallurgie, Mémoires, 1943, vol. 40, May, pp. 143–155; June, pp. 175–182; July, pp. 202–208; Aug., pp. 252–256). Apparatus and the principles on which the recent development of spectrochemical analysis is based are discussed. The precision of the spectrographic methods depends largely on the accuracy in reproducing the results of the measurements; this is needed to establish a true relation between the measured value and the chemical composition of the analysed substance. The evolution of spectrographic apparatus is marked by a wide application of automatic devices which enable the experimental conditions of the analysis to be recorded with great precision.

Colorimetric Determination of Molybdenum in Iron and Steel. M. Kapron and P. L. Hehman. (Industrial and Engineering Chemistry, Analytical Edition, 1945, vol. 17, Sept., pp. 573–576). A photometric method for determining molybdenum in ferrous metals is described. It makes use of water-soluble solvents of low volatility which produce a very stable molybdenum-thiocyanate-complex colour with no necessity for extraction.

Application of Colorimetry to the Analysis of Corrosion-Resistant Steels. L. G. Bricker, S. Weinberg, and K. L. Proctor. (Industrial and Engineering Chemistry, Analytical Edition, 1945, vol. 17, Oct., pp. 661–663). A photometric method for the determination of zinc in corrosion-resistant steels by the dithizone method is presented.

Acid Electric Furnace Carbon Control. C. Locke. (Iron Age, 1945, vol. 117, Oct. 18, pp. 69–71, 176 B). The literature on rapid methods of determining the carbon so as to be able to control heats in electric furnace steelmaking is reviewed, and the relationship between the carbon and ferrous-oxide contents of the bath are discussed.

The Estimation and Influence of Hydrogen in Weld Metal. E. C. Rollason and H. W. Mance. (Welding, 1945, vol. 13, Nov., pp. 436–440, 461). Methods of determining the hydrogen content of weld metal are described with data on the results obtained. The influence of hydrogen in welding and the embrittlement theory is discussed.

The Non-Destructive Testing of Material by the Spot Test. (Spot Tests for Nickel, Cobalt and Iron). R. Weihrich and F. Schwertner. (Archiv für das Eisenhüttenwesen, 1942, vol. 16, Aug., pp. 45–48). Rapid spot tests are described by which the presence of nickel, cobalt and iron in metal can be detected. In these tests a drop of a suitable etching agent is allowed to remain on the surface to be tested for a minute or two; the drop is then absorbed with an impregnated paper and a colour change indicates the presence of the element for which the test is made.

The Application of Drop Reactions on Steels. H. Fucke and M. Möhrle. (Archiv für das Eisenhüttenwesen, 1944, vol. 18, Sept.-Oct., pp. 47–56). Procedures are described for detecting the following elements in steel by means of drop reactions: Aluminium, chromium, cobalt, copper, manganese, molybdenum, nickel, titanium, vanadium and tungsten.

A Composite Method for the Determination of Silicon, Manganese and Phosphorus in Cast Iron and Steel. T. S. Harrison. (Analyst, 1945, vol. 70, Oct., pp. 362–365). A method is described for determining silicon gravimetrically, phosphorus absorptiometrically by the phosphovanadomolybdate technique, and manganese by absorptiometry or titration, all on a single sample of iron or steel.

Absorptiometric Methods of Analysis for 18/8 and Similar Steels. B. Rogers. (Metallurgia, 1945, vol. 33, Nov., pp. 13–16). Using the Hilger Spekker photo-electric absorptiometer, E. J. Vaughan's work has been adapted in the direction of routine methods for the determination of chromium, nickel, manganese, and molybdenum on one sample weight for 18/8 stainless and similar steels containing 12–25% of chromium and 6–14% of nickel.

The Determination of Arsenic in Ferro-Alloys with Special Reference to Ferrotungsten. R. Weihrich and J. Haas. (Archiv für das Eisenhüttenwesen, 1942, vol. 16, Oct., pp. 129–130). When ferrotungsten is dissolved in a mixture of nitric and hydrofluoric acids some of the arsenic is volatilized, but if the sample is first melted with sodium peroxide no arsenic is lost and more accurate arsenic determinations will be made. Details of both procedures are given.

The Determination of Traces of Sulphur Dioxide with Special Reference to the Determination of Sulphur in Ferro-Alloys. G. Ingram. (Analyst, 1945, vol. 70, Nov., pp. 423–426). The method described for the determination of trace amounts of sulphur dioxide was developed to make possible the satisfactory estimation of sulphur in ferro-alloys and organic compounds using the minimum of material, *e.g.*, 10–50 mg. Amounts of sulphur dioxide exceeding 2 μg. can be determined.

New Type Furnace for the Determination of Ash from Coal and Coke. C. W. G. Ockelford. (Fuel in Science and Practice, 1945, vol. 24, Nov.-Dec., pp. 151–157). Developments since 1920 in the design of furnaces used for determining the ash in coal by the Fuel Research Organization method are described and details are given of two modern electric furnaces for temperatures up to 500° and 775° C. respectively.

BOOK NOTICES

(Continued from p. 16 A)

BELCHER, R., and A. L. GODBERT. "*Semi-Micro Quantitative Organic Analysis.*" 8vo, pp. viii + 168. Illustrated. London, 1945: Longmans, Green and Co., Ltd. (Price 10*s*. 6*d*.)

Although semimicro-analysis is a distinct subject in itself, it holds an important intermediate position between macro- and micro-methods, having the dual advantages of requiring less manipulative skill than micro-analysis and of effecting savings in samples, reagents and time, as compared with macro-methods. The purpose of the present book, as pointed out in the preface, is to provide a complete course in the more common methods of this type of analysis, the methods given, it is claimed, being simple and accurate.

The book is divided into four parts. The first part is composed of an introduction to the subject and a general survey of apparatus and technique. This section includes an extraordinarily good chapter "The Balance and Methods of Weighing" from which even well-informed chemists can learn quite a lot about the use and care of the balance. The second part of the book is devoted to the determination of the elements carbon, hydrogen, nitrogen, sulphur, the halogens, phosphorus and arsenic. The first chapter of this section deals with the determination of moisture, ash and metals. Next, there is a short section describing the determination of three of the more important organic radicals—the carboxyl group, the methoxyl group and the acetyl group. The final section is concerned with physico-chemical determinations, limited to the following four properties: density, melting point, boiling point and molecular weight.

In addition to these main sections there are two useful appendices, one being a thorough consideration of the various methods available for the purification of small amounts of material; the other is relatively short and describes the preparation and standardization of seven standard volumetric solutions. There is also appended a bibliography of 46 references.

The book is attractively produced, clearly arranged, and includes 42 diagrams of apparatus drawn with the utmost clarity. It might be mentioned that a more extensive index would have been welcomed. W. W. STEVENSON.

BRITISH NON-FERROUS METALS RESEARCH ASSOCIATION. "*Collected Papers on Metallurgical Analysis by the Spectrograph.*" Edited by D. M. Smith. 8vo, pp. xi + 162. Illustrated. London, 1945: The Association. (Price 21*s*.)

This book, compiled by specialists for the use of specialists, emphasizes the encroachment of purely physical methods upon the classical technique of metallurgical analysis.

Some interest attaches to the Foreword, in which the advantages of co-operative research work become self-evident, especially where association is possible with manufacturers of ancillary materials—in this case, manufacturers of photographic materials.

Much sympathy will be felt for the plea expressed in the Preface for a greater uniformity in technical nomenclature. When experts are not agreed upon the correct description of their methods, assimilation of such progress by technicians in other fields undoubtedly becomes more difficult.

Only non-ferrous metals and their alloys are dealt with in these papers, and the methods recommended appear with precise and detailed items of procedure which are obviously the fruits of close study and considerable experience; one may instance the care taken in preparation of the sample under test (p. 83).

Readers who are mathematically-minded will appreciate frequent allusions to "standard error" and "standard deviation"—evidence of the author's leaning to statistical methods in the assessment of results.

J. FERDINAND KAYSER.

HEDLEY, W. H. "*The Basis of Sheet Metal Drafting.*" 8vo, pp. viii + 118. Illustrated. London, 1945: Longmans, Green and Co., Ltd. (Price 6*s*.)

The purpose of this book is to give a firm foundation in the setting out of patterns, which forms an important part in the technical education of those connected with sheet metal work. Students should find the application of calculations to the development of patterns interesting and valuable.

Although written primarily for students taking the first year senior course of the Northern Counties Technical Council and other similar examining bodies, the book should have a special appeal to the practical metal plate worker; and all interested in handicraft will find it a useful text-book. The contents are as follows: (1) Instruments and Drawing Equipment; (2) Geometrical Constructions using Rule and Compasses; (3) Geometrical Constructions Involving the Use of Drawing-Board, Tee-square, Set Squares, etc.; (4) Orthographic Projection; (5) True Shapes and Sections; (6) Isometric Projection; (7) The Straight Line and Plane; (8) Developments; (9) Triangulation; (10) Intersection of Surfaces and Developments; (11) Developing without Projecting.

VOGEL, A. I. "*A Text Book of Qualitative Chemical Analysis, including Semimicro Qualitative Analysis.*" Third Ed., 8vo, pp. xii + 578. Illustrated. London, 1945: Longmans, Green and Co., Ltd. (Price 12*s*. 6*d*.)

The two previous editions of this book are so well known that the main purpose of this review must be to indicate the alterations and additions that have been made in this third edition. The book is intended to provide a complete course in inorganic qualitative analysis to degree standard, as well as a work of reference for practical analytical chemists.

The first chapter, which is an excellent one, on the theory of qualitative analysis remains unchanged, whilst only a few minor modifications, in the microchemical section, have been made to the second chapter on "Analytical Operations," which is a well-designed introduction to experimental technique. The next two chapters, which deal in detail with the reactions of metal ions and acid radicals respectively, remain substantially unaltered. Chapter V., describing the "Systematic Analysis of Inorganic Substances," has been considerably extended to give a more complete account of the examination for acid radicals. Chapter VI. is concerned with the modifications in analytical methods required in the presence of organic acids, silicates, borates, fluorides and phosphates. The reactions of the so-called rarer elements are dealt with in Chapter VII.

Here follow two completely new chapters. Chapter VIII., for elementary students, describes a systematic qualitative analysis of inorganic substances. In view of the number of elementary books on the subject, this chapter does not appear to be a necessary addition to the present volume.

Chapter IX. is devoted to semimicro-methods and is a most welcome addition. The first 23 pages are devoted to an introduction to the new experimental technique required, whilst the remaining 33 pages provide a systematic scheme for semimicro qualitative analysis.

The Appendix contains such information as is to be expected in a book on this subject, together with some model analyses for the guidance of students.

One minor criticism concerns the method of cross-reference, by section numbers instead of page numbers, which is not conducive to quick reference.

W. W. STEVENSON.

BIBLIOGRAPHY

Acid Open-Hearth Research Assoc. Inc. Bulletin No. 1. "*Acid Open-Hearth Slag Fluidity and its Significance.*" By G. R. Fitterer, J. W. Linhart, B. B. Rosenbaum, J. B. Kopec, S. Poch, W. G. Wilson. 8vo, pp. vi + 60. Pittsburgh, 1945 : The Association. (Price $1.00.)

American Institute of Mining and Metallurgical Engineers. "*Proceedings of the Twenty-Eighth Conference National Open-Hearth Committee of the Iron and Steel Division.*" Vol. 28, 8vo, pp. 478. Illustrated. New York, 1945 : The Institute.

American Society for Testing Materials and American Institute of Mining and Metallurgical Engineers. "*Symposium on Stress-Corrosion Cracking of Metals.*" Held at Philadelphia, Pa., Nov. 29–30 and Dec. 1, 1944. 8vo, pp. viii + 495. Illustrated. Philadelphia, 1945 : A.S.T.M.; New York : A.I.M.M.E. (Price $5.50.)

Berdrow, W. "*Alfred Krupp und sein Geschlecht.*" 8vo, pp. 320. Berlin, 1943 : Verlag für Sozialpolitik, Wirtschaft und Statistik, Paul Schmidt. (Price 3.85 RM.)

British Standards Institution. "*Recommendations on Methods of Protection against Corrosion for Light Gauge Steel and Wrought Iron used in Permanent Building Construction.*" P.D. 420, November, 1945. 8vo, pp. 8. (Price 1*s.*)

British Standards Institution. B.S. 667 : 1945. "*Photoelectric Type Portable Photometers.*" 8vo, pp. 9. London : The Institution. (Price 2*s.*)

Cazaud, R., and L. Persoz. "*La Fatigue des Métaux.*" By R. Cazaud and L. Persoz. Préface by A. Caquot. Deuxième Édition. 8vo, pp. xii + 259. Illustrated. Paris, 1943 : Dunod. (Price 262 francs.)

Cowdrey, I. H., and R. G. Adams. "*Materials Testing : Theory and Practice.*" Second ed. 8vo, pp. vii + 156. New York : John Wiley and Sons, Inc.; London : Chapman and Hall, Ltd. (Price 10*s.* 6*d.*)

Durrer, R. "*Verhütten von Eisenerzen ausser dem Verhütten im Kokshochofen.*" (Stahleisen-Bücher. Bd. 3). 8vo, pp. xii + 133. Illustrated. Düsseldorf, 1943 : Verlag Stahleisen, m.b.H. (Price 12.40 RM.)

Gumz, W. "*Die Kohle.*" (Handbücherei des Kohlenkaufmanns. Hrsg. vom Beauftragten für den Kohlenhandel in der Reichsgruppe Handel in Zusammenarbeit mit den Fachgruppen Kohlengrosshandel und Kohleneinzelhandel). (Bd. 1). 4to, pp. 172. Illustrated. Berlin, 1943 : Verlag Deutsche Kohlenzeitung, Wilhelm Ohst. (Price 6 RM.)

Guzzoni, G. "*Gli acciai comuni e speciali.*" 3 edizione completamente rifatta ed ampliata. 8vo, pp. xvii + 889. Milan, 1943 : Ulrico Hoepli.

Hedley, W. H. "*The Basis of Sheet Metal Drafting.*" 8vo, pp. viii + 118. Illustrated. London, 1945 : Longmans, Green and Co., Ltd. (Price 6*s.*) (*See* p. 35 A).

Hilbert, H. "*Stanzereitechnik.*" 2 Auflage. Bd. 1, "*Schneidende Werkzeuge, Arbeitspläne, Entwurf und Herstellen der Werkzeuge, Maschinen zum Schneiden, Kalkulation von Werkzeugen und Schnitteilen.*" 8vo, pp. 312. München, 1942 : Carl Hanser Verlag. (Price 7.80 RM.)

Institute of British Foundrymen. "*Methods of Testing Prepared Foundry Sands.*" First Report of the Joint Committee on Sand Testing. 8vo, pp. 36. Illustrated. Manchester, 1945 : The Institute. (Price : Gratis to members of the co-operating organizations; 10*s.* 6*d.* to non-members.)

Jarvis, E. G., and H. O. Jarvis. "*Facts for Foundrymen.*" Fifth ed. 8vo, pp. 80. Buffalo, N.Y. : Niagara Falls Smelting and Refining Corp. (Price $1.00.)

Josch, K. "*Gusseisen als Baustoff.*" 8vo, pp. 79. Illustrated. Stuttgart, 1943 : Franckh'sche Verlagshandlung. (Price 3.60 RM.)

Kirkstall Forge. "*The History of the Kirkstall Forge Through Seven Centuries* 1200–1945 A.D." 4to, pp. vii + 152. Illustrated. Kirkstall, 1945 : Henry Jenkinson, Ltd. (Price 25*s.* Copies can be obtained from Kirkstall Forge, Ltd., Leeds.)

Kornilov, I. I. "*Iron Alloys.*" Vol. 1. "*Iron-Chromium-Aluminium Alloys.*" (Academy of Sciences, U.S.S.R.). 8vo, pp. 192. Illustrated. Moscow, 1945.

Mayenborn, R. "*Untersuchungen über das unterschiedliche Durchvergütungsvermögen von Baustählen.*" (Aachen (Techn. Hochschule), Dr.-Ing.-Diss.). 4to, pp. 26. Illustrated.

Miess, A. "*Die Ueberspannung der Eisenmetalle.*" [Fe, Co, Ni]. (Berlin (Techn. Hochschule), Dr.-Ing.-Diss.). 4to, pp. 70. Illustrated.

Ministry of Supply. "*A First Guide to Quality Control for Engineers.*" By Dr. E. H. Sealy. London : H.M. Stationery Office. (Price 1*s.*)

Nelson, J. H., and H. Silman. "*The Application of Radiant Heat to Metal Finishing.*" Second ed. 8vo, pp. 91. London, 1945 : Chapman and Hall, Ltd. (Price 8*s.* 6*d.*)

Pull, E. "*Boiler House Practice.*" Second ed. 8vo, pp. 288. Kingston Hill, 1945 : Technical Press, Ltd. (Price 10*s.* 6*d.*)

Ruf, J. "*Die Berechnung der Schwere- und Temperaturseigerung bei flüssigen zweistofflegierungen.*" (Stuttgart (Techn. Hochschule), Dr.-Ing.-Diss.). 4to, pp. 47.

Sawert, W. "*Die Festigkeit der Baustähle bei wechselnder mehrachsiger Beanspruchung.*" (Berlin (Techn. Hochschule), Dr.-Ing.-Diss.). 4to, pp. 39.

Schenck, H. "*Introduction to the Physical Chemistry of Steelmaking.*" Translated by H. J. Goldschmidt for the British Iron and Steel Research Association. 8vo, pp. xvi + 587. Illustrated. London, 1945 : The British Iron and Steel Research Association. (Price £3 10*s.*)

Schmitz, F. "*Ein Beitrag zur Frage der Lötbrüchigkeit von Stahl.*" (Aachen (Techn. Hochschule), Dr.-Ing.-Diss.). 4to, pp. 31. Illustrated.

Society of Automotive Engineers, Inc. "*S.A.E. Handbook. 1945 Edition.*" 8vo, pp. lxiii + 806. Illustrated. New York City, N.Y. : The Society.

Tak-Ho Sun, B. S. "*Ueber den Wasserstoff im Stahl.*" (Aachen (Techn. Hochschule), Dr.-Ing.-Diss.). 4to, pp. 99. Illustrated.

Tibbenham, L. "*The Welding of Cast Iron by the Oxy-Acetylene Process.*" Second ed. London : Sir Isaac Pitman and Sons, Ltd. (Price 7*s.* 6*d.*)

United Steel Companies, Ltd. "*Standard Methods of Analysis of Iron, Steel and Ferro-Alloys.*" As used by the Laboratories of The United Steel Companies, Ltd. Third Ed. 8vo, pp. vii + 93. Sheffield, 1945 : The United Steel Companies, Ltd. (Price 7*s.* 6*d.*)

Verein deutscher Ingenieure. "*Schweissen von Gusseisen.*" Hrsg. vom VDI-Fachausschuss für Schweisstechnik. 8vo, pp. viii + 152. Illustrated. Berlin, 1943 : VDI Verlag, G.m.b.H. (Price 6 RM.)

Warbichler, P. "*Ausarbeitung eines Abdruckverfahrens zum Nachweis von Phosphorseigerungen in Eisen und Stahl.*" (Graz (Techn. Hochschule), Dr.-Ing.-Diss.). 4to, pp. 71. Illustrated.

Woldman, N. E., and R. J. Metzler. "*Engineering Alloys.*" Second ed. 8vo, pp. 833. Cleveland : American Society for Metals. (Price $10.00.)

Zworykin, V. K., G. A. Morton, E. G. Ramberg, J. Hillier and A. W. Vance. "*Electron Optics and the Electron Microscope.*" 8vo, pp. xi + 765. Illustrated. New York, 1945 : John Wiley and Sons, Inc.; London : Chapman and Hall, Ltd. (Price $10.00.)

MINERAL RESOURCES

(Continued from p. 1 A)

The Coking Coal Resources in the Yorkshire, Nottinghamshire and Derbyshire Coalfield. R. A. Mott. (Transactions of the Institution of Mining Engineers, 1945, vol. 104, June, pp. 446–468).

The Lancashire Coalfield. N. Simpkin. (Institute of Fuel War Time Bulletin, 1945, Dec., pp. 54–63). A general description and a survey of the history of the Lancashire coalfield are given; these cover its geological structure, coal seams, lower coal measures, output, and types and analyses of coal.

The Grand Lake Coal Field. N.B. W. J. Wright and C. S. Clements. (Transactions of the Canadian Institute of Mining and Metallurgy, 1945, vol. 48, Dec., pp. 747–754). A description is given of the geology and present state of development of the Grand Lake coalfield of central New Brunswick from which 368,544 short tons of bituminous coal were mined in 1943.

The Production of Both Coking and Steam Coals from the Witbank Coalfield. L. A. Bushell, S. B. Gass, F. W. Quass, and R. F. J. Teichmann. (Journal of the Chemical, Metallurgical and Mining Society of South Africa, 1945, vol. 46, July-Aug., pp. 45–59). Results of some float-and-sink analyses and coking tests on coking and steam coals from the Witbank coalfield in South Africa are reported and discussed. It is shown that the reserves of coking coal are small, but by the immediate introduction of blending and other economic measures the life of the reserves could be increased to about 163 years.

Gold-Coast Manganese. (Iron and Steel, 1945, vol. 18, Nov. 30, pp. 536–539). A brief and well-illustrated description is given of the open-cast workings of the manganese ore deposits at Nsuta in the Western Province of the Gold Coast. There are a washing plant and mechanical units to crush and grade the ore.

ORES—MINING AND TREATMENT

Process Measures in the Sintering of Iron Ores. K. Kintzinger. (Stahl und Eisen, 1943, vol. 63, June 10, pp. 453–456). An account is given of laboratory and full-scale investigations of methods of improving the unsatisfactory output of German sintering plants. Increasing the suction in the range of 600–1600 mm. of water was tried, and the optimum suction was found to be at about 1200 mm. Improvements were also obtained by mixing ground burnt lime with the charge.

Principles of Iron Ore Beneficiation and Their Effects on Blast-Furnace Operation. C. E. Agnew. (Steel, 1945, vol. 117, Nov. 26, pp. 124–126, 144–158; Dec. 3, pp. 134, 170–186; Dec. 10, pp. 122–126, 144; Dec. 17, pp. 125–128, 164–168). The thermal principles of blast-furnace operation as applied to the use of sinter were dealt with previously (*see* Journ. I. and S.I., 1944, No. I., p. 42 A). In this paper the beneficiation of ores by sintering, and by making nodules, briquettes and pellets is described. The properties of the products are discussed. The effect of the chemical composition of the slag on the thermal requirements of the hearth and bosh are also dealt with.

New Magnetic Concentrator Treats Mt. Hope Iron Ore. H. Davenport. (Engineering and Mining Journal, 1945, vol. 146, Sept., pp. 85–89). An illustrated description is given of the plant for concentrating the iron ore at the Mount Hope Mine, Wharton, New Jersey. In view of the heavy demand for high-grade lump magnetite, the new concentrator produces approximately two-thirds of the concentrates in the lump-ore plant and one-third by wet magnetic concentration in the fine-ore plant.

FUEL

(Continued from p. 17 A)

Theoretical Limiting Efficiency of Various Fuels in the Open Hearth. B. M. Larsen and C. Siddall. (Iron and Steel Engineer, 1945, vol. 22, Dec., pp. 76–95). A detailed theoretical consideration governing the selection and use of fuels for the open-hearth furnace is presented. Thermal data and examples of calculations are also given.

Blast-Furnace Gas and Oxygen-Enriched Air for the Open-Hearth Furnace. G. Bulle. (Zeitschrift des Vereines deutscher Ingenieure, 1940, vol. 84, Sept. 28, pp. 740–741). As the cost of producing oxygen has been reduced considerably by the Linde-Fränkl process, tests were made to determine the applicability of mixtures (*a*) of blast-furnace gas and oxygen, and (*b*) of blast-furnace gas and oxygen-enriched air for steelmaking in the open-hearth furnace. A horizontal cylindrical furnace 2 m. long with a capacity of 100 kg. of steel was used. The charges were easily melted with either of the above mixtures (the fuel gases being heated in recuperators), and the data obtained were sufficiently encouraging for a larger experimental plant to be built.

Fuel Problems in the Swedish Iron and Steel Industry. M. Tigerschiöld. (Iron and Steel Institute, 1946, this Journal, Section I.). The evolution of the Swedish iron and steel industry and the mineralogical, historical, and economic factors affecting that evolution are briefly discussed. The occupation of Norway by the Germans in 1940 completely isolated Sweden

from British and American sources of imports; with little or no suitable native resources of coal, coke, petrol or fuel-oil, the position of Swedish industry in regard to fuel supplies was critical. Fuel economy became a paramount necessity and industry went over to the use of substitutes, such material as wood, charcoal, and pressed-straw bales being used as metallurgical fuels. Equipment and methods were altered and new equipment and methods were devised to meet the situation, with striking results.

Fuel Utilization in Iron and Steel Works. N. H. Turner and F. A. Gray. (Iron and Steel Institute, 1946, this Journal, Section I.). Problems met with in current fuel-utilization practice at integrated and non-integrated iron and steel works are briefly discussed. These problems are chiefly concerned with blast-furnace gas production, cleaning, and distribution; some remarks as to the effect on fuel utilization of possible future modifications in blast-furnace practice have been added. The application of by-product gases to steelworks uses and the general question of heat conservation are also considered. A comparison is made of the operating results at the melting shops and mills of the Appleby and the Templeborough Works. The paper concludes with some indication of what has been achieved, in respect of fuel economy, at certain subsidiary plants of The United Steel Companies, Ltd.

Operating Results of Dry-Cooling Plants. (Coke and Smokeless Fuel Age, 1946, vol. 8, Jan., pp. 10–11). The dry cooling of coke has been developed in Switzerland on a considerable scale. In this short article two tables are presented by the Swiss Association of Gas Engineers giving the characteristics and operating results of twenty dry-cooling plants.

Upgrading Coke-Oven Gas. G. Cellan-Jones. (Coke and Smokeless Fuel Age, 1946, vol. 8, Jan., pp. 8–9). A method of increasing the benzole yield from coke-oven gas by introducing stripped gas into the oven crown is described.

Gaseous Fuels in Britain. D. D. Howat. (Chemical Age, 1946, vol. 54, Jan. 26, pp. 107–111; Feb. 2, pp. 133–137). The efficient utilization of town gas, coke-oven gas, blast-furnace gas, and producer gas in Great Britain is discussed.

Operational Experience with a Gas-Producer Plant with Subsequent Electric Gas Cleaning. E. Pechal. (Iron and Steel Institute, 1946, Translation Series, No. 265). This is an English translation of a paper which appeared in Stahl und Eisen, 1943, vol. 63, Nov. 4, pp. 808–812 (*see* Journ. I. and S.I., 1945, No. II., p. 178 A).

PRODUCTION OF IRON

(Continued from p. 18 A)

Designs of Withdrawal Lugs for Blast-Furnace Cooling Plates. J. K. Reay and R. P. Towndrow. (Iron and Coal Trades Review, 1946, vol. 152, Jan. 4, pp. 16, 15). A design is published of a lug, cast integrally with copper cooling plates for blast-furnaces, which is capable of withstanding a direct pull of about 25 tons.

Smelting Iron Ore in the Electric Low-Shaft Furnace. M. A. Kassen. (Schweizer Archiv, 1945, vol. 11, Mar., pp. 87–93). The control of the Tysland-Hole electric furnace for making pig-iron is discussed. The method of controlling the silicon by adjusting the coke in the burden, which is applied in blast-furnace operation cannot be applied in the electric process, but silicon control by adjustment of the amperage/voltage ratio is possible. The method is dealt with fully in this paper.

The Höganäs Sponge Iron Process. S. Eketorp. (Svenska Teknologförening: Jernkontorets Annaler, 1945, vol. 129, No. 12, pp. 703–721). (In Swedish). A description is given of the history and present stage of development of the Höganäs process of making sponge iron. It consists of charging ceramic pots about 5 ft. high, made of a local fireclay, with flat briquettes of a concentrate containing 71·5% of iron interspersed with layers of carbon prepared by mixing Höganäs coal with coke breeze; the pots are charged in batches in a long pit furnace where they are heated to about 1200° C., the total time in the furnace being about 12 days. The pots are emptied by manual labour and put on a conveyor which takes them to tumbling machines where the ash and dirt are removed. The furnace is large enough to take 35,000 pots. The process has been in operation since 1911, and production is now at the rate of about 20,000 tons/annum. The product contains 97·2% of iron, 0·009% of sulphur and 0·011% of phosphorus. As produced, the sponge-iron blocks have a density of 2·0, but if they are compressed into briquettes the density is about 3·5.

A brief account is given of the use of this sponge iron in steelmaking. In a trial at Surahammar a charge of 100% briquettes was melted in a basic-lined high-frequency furnace and the wear on the lining was not abnormal. In acid-lined furnaces it was not possible to charge more than 20% briquettes until the experiment of making the sponge iron with a certain amount of silicon was tried, which reduced the lining wear to normal.

The Krupp-Renn Process. (Metal Treatment, 1945, vol. 12, Winter Issue, pp. 263–271). Brief descriptions of the Walz and Renn rotary furnaces and the results of trial smelting runs in which the Krupp-Renn process is used in three different applications are given. The first application is the production of "pellets" for charging directly into the open-hearth furnace; the second is the production of pellets for the blast-furnace; and the third is the production of non-ferrous metals such as nickel, copper, silver, and cobalt, in each case with iron as well.

Powder Metallurgy of Iron. G. H. S. Price. (Metal Treatment, 1945, vol. 12, Winter Issue, pp. 275–286, 274). A comprehensive review of the literature on the powder metallurgy of iron is presented.

FOUNDRY PRACTICE

(Continued from pp. 18 A–21 A)

Cast Iron Foundry Practice. United States Wartime Developments. J. S. Vanick. (Association Technique de Fonderie : American Foundryman, 1945, vol. 8, Nov., pp. 57–67). The progress made in American foundries in the period 1940 to 1945 to increase production is described and illustrated. Special reference is made to the turntable system of moulding and casting.

Some Thoughts on Foundry Management. J. R. Roxburgh. (Institute of British Foundrymen : Foundry Trade Journal, 1946, vol. 78, Jan. 24, pp. 75–81). Principles of good works management are expounded, and it is stressed that executives should possess the greatest possible degree of practical experience in the foundry. Some of the problems appertaining to foundry management, *e.g.*, time and motion study, production control, costing, and working conditions, are separately dealt with.

Cast Steel. (Iron and Steel, 1945, vol. 18, Dec., p. 628). Thorough deoxidation with a view to minimizing porosity, internal tears, low ductility, and poor surfaces, is easily accomplished by the use of silicomanganese and calcium alloys. To assure consistently good results a uniform furnace procedure is necessary ; such a procedure is outlined.

Malleable Sand Control in a Large Mechanized Foundry. J. J. Clark. (American Foundryman, 1945, vol. 8, Nov., pp. 49–56). A description is given of the equipment and the tests designed to enable good moulding sand and cores to be furnished to the foundry. The importance of proper maintenance and operation of the equipment is stressed.

Sand Supply to Moulding Machines from Overhead Hoppers. N. C. Blythe. (Institute of British Foundrymen : Foundry Trade Journal, 1946, vol. 78, Jan. 3, pp. 9–11). The design of suitable hoppers which give satisfactory service under the severe conditions of the moulding shop is discussed. A type of hopper is suggested which provides an operator with sand every time he wants it. A distribution conveyor to take care of the hopper's failings in capacity is also described.

The Application of Ethyl Silicate to Foundry Practice. C. Shaw. (Institute of Britsh Foundrymen and the Institute of Metals : Foundry Trade Journal, 1946, vol. 78, Jan. 10, pp. 31–33). Refractory bodies can be produced by using silicon esters as a binder for refractory aggregates. When fully hydrolysed, the addition of an alkali to the liquid ethyl silicate will so shorten the time of gelatinization that, by varying the amount of alkali, the cement will set after a predetermined time. Certain substances, the nature of which is not disclosed, promote the formation of strong gels and sound moulds, the hydrolysis going on in the mould. The setting time may be varied between 5 min. and 5 hr., according to the amount of water added and the concentration of the agent. Many uses for this method in the foundry industry are recommended, and it is suggested that many moulding problems can be solved by taking advantage of the controlled setting time, the dimensional stability during setting and baking, and the high mechanical strength. Moulding from wax patterns and the " semi-dry piece mould " are also described.

Patternmaking for Small Batch Machine-Moulded Castings. A. G. Squires. (Institute of British Foundrymen : Foundry Trade Journal, 1946, vol. 78, Jan. 10, pp. 35–37). A method of preparing moulds for small batches of similar castings where half of the pattern will fall below the face of the moulding plate is described. It comprises a pair of pattern plates with six plaster patterns matched and produced from a single master pattern.

Pattern Redesign for Increased Production. E. C. Moorhead. (American Foundryman, 1945, vol. 8, Nov., pp. 26–28). In many foundries where castings are made from an original pattern over long periods production could in many cases be greatly increased by minor changes in pattern design and equipment without necessarily changing the casting itself. Recommendations on redesigning patterns and simplifying moulding are made.

Quantity Floor Moulding—Manufacture of Medium Bore Flanged Return Bends. I. H. List. (Iron and Steel, 1945, vol. 18, Dec., p. 646). Sketches show the pattern for medium-bore flanged return bends and a cross-section through the mould. Details of the mould and moulding operation are given.

The Influence of Radiation within Molding Sand on the Freezing Rate of Metal. H. A. Schwartz. (American Foundryman, 1945, vol. 8, Nov., pp. 45–48). A mathematical and theoretical treatment of the heat transfer within moulding sand is presented. The relationship between the amount of metal which freezes in a sand mould and time cannot be satisfactorily explained if it is assumed that the thermal conductivity of sand is independent of temperature. In this paper calculations are put forward which indicate that the transfer of heat through sand takes place partly by conduction and partly by radiation.

Steel Castings Repair Methods. J. F. Cotton. (American Foundryman, 1945, vol. 8, Nov., pp. 29–34). Various methods of examining and removing defects in steel castings are described. Guidance is given for deciding whether repair is necessary or desirable and on how the repair should be effected.

Flame-Gouging of Steel Castings. A. E. Blake, jun. (Engineering Materials and Processing Methods, 1945, vol. 22, Nov., pp. 1428–1431). The technique for the removal of defective areas from steel castings by flame-gouging with a burner using town gas and oxygen is described.

Notes on Inspection. R. J. Hart. (Institute of British Foundrymen : Foundry Trade Journal, 1946, vol. 78, Jan. 3, pp. 3–8, 21). The methods employed in routine inspection, both of pattern equipment and castings (mainly steel castings), are outlined and illustrated. Apart from the object of inspection, the principal points discussed are : Inspection of patterns and samples, bulk inspection, physical testing, and delegated inspection.

PRODUCTION OF STEEL

(Continued from pp. 21 A–22 A)

Soviet Iron and Steel. Main Trends of Developments in the New Five Year Plan. I. Bardin. (Iron and Steel, 1945, vol. 18, Dec., pp. 657–658). The immediate aims and objects of the Russian steel industry are outlined, and it is implied that the U.S.S.R. aims at self-sufficiency in ferrous materials. Principles of managing iron and steel plants are put forward, and it is emphasized that obsolete plants should be discarded, although they may be in a good state of repair. With a view to establishing a minimum number of types of blast-furnace, standardization of plant and equipment generally is envisaged.

The German Steel Industry. T. W. Lippert. (Iron Age, 1945, vol. 156, Dec. 20, pp. 54–59). A detailed account is given of plant, processes, labour employed and the working conditions in German steelworks during the last war. High production was ensured by imported labour and some technical innovations. An all-basic open-hearth furnace practice was used. Among the technical improvements the number of cranes and charging machines was surprisingly large; and the health service for German labour was of a high standard although safety precautions were of a low order.

General Review of German Metallurgical Practices. J. H. Frye. (Metal Progress, 1946, vol. 49, Jan., pp. 76–86). In 1945 the author examined many of the German metallurgical plants and processes and in this review he reports on the state in which he found them and on the changes and developments which had taken place during the war years. He compares the efficiency of the processes and products with those obtaining in the United States.

Advancements in the Metallurgical Sphere in the United States during the War. A. Grønninsæter. (Norsk Metallurgisk Selskap: Jernkontorets Annaler, 1945, vol. 129, No. 12, pp. 683–702). (In Norwegian). This paper, which has appeared in Tidsskrift for Kjemi og Bergvesen, reviews the technical advancements in the production of iron and steel, sulphur, manganese, copper, lead, zinc, chromium, aluminium, magnesium and the ferro-alloys, which have taken place in the United States in the period 1940–1945. Methods of concentrating ores are also dealt with.

Electric Power in a Steel Plant. R. W. Graham. (Electrical Engineering, 1945, vol. 64, Dec., pp. 816–818). A brief description is given of the system adopted by the Bethlehem Steel Company for the distribution of electric power at their Lackawanna plant.

Proceedings of the Twenty-Eighth National Conference on Open-Hearth Steel. (American Institute of Mining and Metallurgical Engineers, Open-Hearth Conference, Apr.-May, 1945). In order to economize in transport and hotel accommodation it was decided to hold four local conferences at Philadelphia (Apr. 20), Chicago (Apr. 27), St. Louis (May 4), and Pittsburgh (May 18), respectively, instead of one large meeting at Chicago as originally intended.

Two special papers are given, namely "Melt Control, Its Evolution and the Effect of a Current Control Method on Basic Open-Hearth Operations" for which the author, A. M. Kroner, received the McKune award, and "Operation of an Experimental Open-Hearth Furnace" by H. K. Work and W. R. Webb (*see* Journ. I. and S.I., 1945, No. II., p. 136 A). Kroner's paper describes a method of calculating the hot-metal additions for open-hearth furnaces which takes the following factors into account: (*a*) The percentage of iron in the metallic charge; (*b*) the amounts of scrap, cold iron, limestone and ore charged; (*c*) the silicon content of the hot metal; and (*d*) the time elapsing between starting to charge cold metal and finishing the hot-metal addition.

The Pittsburgh meeting, which dealt with refractories for open-hearth furnaces, is next reported. This began with a report by H. M. Griffith on the operation, and condition after 500 heats, of an all-basic-lined 180-ton open-hearth furnace of the Steel Company of Canada. Experiences with all-basic-lined open-hearth furnaces were related by H. S. Frank and A. E. Reinhard, and R. B. Sosman presented a paper on "The Outlook for an All-Basic Open-Hearth Furnace." After a brief discussion of silica-brick roofs, M. A. Fay dealt with a new theory on the mechanism of wear of these roofs which is that the wear of roof bricks is caused by liquid flowing from a considerable distance within the brick. The merits of bonded and of ribbed roofs, and mullite refractories were discussed, and W. S. Debenham presented an analysis of the replies to a questionnaire on open-hearth bottom construction and materials. R. B. Snow discussed data obtained from density tests on material removed when renewing hearths. A very comprehensive paper on "Nozzle and Stopper-Head Properties, Pouring Techniques, and Their Effect on Casting-Pit Performance" was delivered by L. G. Ekholm and L. D. Hower, jun. After short addresses by J. A. Shea on "Methods of Testing Stoppers" and L. R. Berner on "Lining and Scheduling Ladles for Maximum Life," the Pittsburgh meeting closed with a discussion on the storage of refractory bricks.

The meeting at Philadelphia dealt with the maintenance and repair of basic open-hearth furnaces. C. D. Moore began by explaining how the Worth Steel Company planned their furnace-repair programme. The maintenance of roofs was discussed, and two papers were then presented, one by O. P. Luetscher on "Life and Maintenance of Open-Hearth Roofs," and the other by E. N. Hower on "Hot Patching of Open-Hearth Furnaces." Open discussions on the maintenance of bottoms, tap-hole repairs, and fettling time followed; at the end of this section of the Proceedings a summary is given of the answers to a questionnaire on the times taken for open-hearth bottom maintenance.

The Chicago meeting discussed the operation of open-hearth furnaces. The following papers were presented: "Residual Metals in Open-Hearth Steel"

by J. D. Sullivan and A. E. Pavlish; "Segregation of Scrap at Wisconsin Steel Works" by E. H. Schwartz; "A Completely Automatic Control of Open-Hearth Reversal" by B. M. Larsen and W. E. Shenk; "Stoppers and Nozzles" by J. P. L. McMahon; "Nozzle Size *vs.* Quality of Hot-Top Ingot" by H. J. Forsyth; "Factors in Mold Design for Big-End-Up Molds" by G. Soler; "Effect of Variables on Surface and Yield of Medium Carbon Semikilled Steel" by E. C. Sorrells; "Effect of Furnace, Pit, and Mold Practice on Surface and Yield of Semikilled Ingots" by J. R. Britt; "Factors Affecting Efficiency of Aluminium Additions to Fine-Grained Steel" by R. C. Diehl; "Measurement and Control of Open-Hearth Flame Radiation Intensity at Gary Steel Works" by A. L. Hodge; and "A Method of Determining Bath Temperatures" by L. F. Weitzenkorn. In addition to the above there were open discussions on improvements in charging practice, furnace-control systems, aluminium recovery, burners for liquid and mixed fuels, colloidal fuel, and flame radiation. At this meeting there was also a session on metallurgy and quality; it began with the presentation of summaries of the following papers which were to have been read at the Deoxidation Symposium in New York in February, 1945: "Effect of Deoxidation on the Strain-Sensitivity of Low-Carbon Steels" by H. K. Work and G. H. Enzian; "The Relation among Aluminium, Sulphur and Grain Size" by C. E. Sims; and "Occurrence of Oxygen in Liquid Open-Hearth Steel—Sampling Methods" by T. E. Brower and B. M. Larsen. It was continued with two papers on the economic aspects of deoxidation, one by M. Tenenbaum and the other by R. C. Diehl and F. G. Norris, and a paper by K. L. Fetters on the deoxidation of coarse-grained steels. The other papers contributed at this session were: "Elimination of Surface Defects in Low-Carbon Low-Sulphur Silicon-Killed Steel of S.A.E. 1020 Specification" by O. Pearson; "Improving Cleanness of Killed Steel" by S. Feigenbau; "Variables in Producing Clean Steel in Large Tonnages" by C. L. Labeka; "The Chemistry of Slag Control" by H. B. Emerick; "Review of Recent Developments in Basic Open-Hearth Slag Control" by M. Tenenbaum; and "Hardenability Bands and the Open-Hearth Factors Controlling Hardenability" by C. G. Atchinson. Open discussions also took place on the cleanness of killed steel, slag control, subsurface porosity, and hardenability.

The Acid Open-Hearth Technical Session was held on May 18, 1945, at Pittsburgh. One paper was presented; this was by C. E. Wenninger and W. McCaulley on the steps taken at a steel foundry to improve acid open-hearth practice. The remainder of this session was taken up with open discussions on a variety of subjects including the effect of mould life on defects on machined forgings, the sand requirements for repairing bottoms and banks, whether it is better to make additions on a rising or a falling temperature, whether additions of alloying elements should be made to the furnace or the ladle, the life of the front and back walls in 25-, 50- and 75-ton furnaces, the castability of acid open-hearth steel, the relation of furnace practice to the prevention of hot-tear formation, adding graphite instead of pig-iron to provide the carbon in acid open-hearth steel, reboiling acid open-hearth steels for forgings, the values of raw and burnt-lime additions to acid open-hearth slags.

The Manufacture of High Speed Steel. W. H. Wills. (Steel Processing, 1945, vol. 31, Nov., pp. 703–708). High-speed steel may be divided into two groups, namely, the tungsten and the molybdenum types. Electric-arc furnaces of from 3 to 6 tons are used in the melting of tool steels, the charge being melted in 2 hr. under a reducing slag. The subsequent stages of manufacture include hammer-cogging, grinding, hot-rolling, forging, annealing, and cold-drawing to sizes less than 1 in. in dia. After drawing, a final annealing is necessary before straightening; small sizes are sheared, larger bars are sawn to length.

Final Additions to an Acid Electric Heat. C. C. Wissmann. (Metal Progress, 1945, vol. 48, Dec., pp. 1296–1299). A practice for working an acid electric-furnace heat of steel is outlined with special stress on the best time to make the additions of ferro-alloys.

Industrial Electrodes. H. Sanders. (British Steelmaker, 1945, vol. 11, June, pp. 255–259; July, pp. 303–307; Aug., pp. 359–363; Sept., pp. 409–412). A comprehensive account is given of the development of the manufacture of carbon and graphite electrodes, their properties, and their application in metallurgical furnaces. Recommendations to prevent wastage in electrode consumption are made.

Big Crucible Ingots. (British Steelmaker, 1945, vol. 11, Dec., pp. 554–556). A description is given of the scene in a Sheffield melting shop in the eighteen-eighties during the casting of a 30-ton ingot from nearly 1000 crucibles each of which had been charged with 70 lb. of bar iron.

Crucible Failure in the Induction Melting Process. A. Gemant and J. Sticher. (Journal of Applied Physics, 1945, vol. 16, Nov., pp. 661–667). Experience shows that, in the course of the induction melting process, local overheating of the crucible sometimes occurs, which in extreme cases leads to failure. This is probably due to thermal instability. Overheating is more probable when the crucible material has a steep electrical-resistivity/temperature characteristic—a condition which may be caused by impurities. Computations are made showing the transition from stable to unstable conditions in the operation of an experimental and an industrial furnace and equations are developed which facilitate the selection of a current frequency which will ensure that the crucible temperature does not rise above the stable range.

Acid Open-Hearth Steel. J. R. Rait. (British Iron and Steel Research Association: Iron and Steel, 1945, vol. 18, Dec., pp. 647–654). Factors influencing the formation of non-metallic inclusions in acid open-hearth steel are discussed. The following conclusions are arrived at respecting the deoxidation of this steel: (1) The addition of silicon before manganese must be avoided because, during solution, the highly concentrated silicon streaks react with oxygen to form

refractory particles of almost pure silica; a subsequent addition of manganese is almost ineffective for deoxidation. (2) If silicon is added after manganese, it is important that the manganese/silicon ratio should not fall below 4 : 1; the time factor between the additions is therefore extremely critical. (3) The use of silicomanganese alloys, with the elements present in the correct ratio, is the surest method of producing fluid FeO–MnO–SiO_2 deoxidation products. The relative merits of finishing with a high or a low FeO content in the slag are discussed. In conclusion, casting-pit refractories as a source of non-metallic inclusions are considered.

Acid Open Hearth Slag Fluidity and Its Significance. G. R. Fitterer, J. W. Linhart, B. B. Rosenbaum, J. B. Kopec, S. Poch, and W. G. Wilson. (Acid Open Hearth Research Association, Sept., 1945, Bulletin No. 1). The Acid Open Hearth Research Association was established in 1942 by a group of American companies manufacturing acid open-hearth steel, for studying their problems by co-operative research. In this bulletin, practical methods of measuring slag fluidity and a standard fluidity test for acid open-hearth slags are described. The significance of the test is discussed. As the slag fluidity decreases during a heat, the silica content of the slag increases, the ferrous-oxide content and density decrease, and the temperature of the metal increases. A simple control procedure based on these relationships and the slag-fluidity test is described. There are two appendices, one on the theories of viscosity, and the other on laboratory determinations of slag density. A bibliography of 81 references is added.

The Reduction of Silica by Liquid Steel. W. Geller. (Iron and Steel Institute, 1946, Translation Series, No. 266). This is an English translation of a paper which appeared in Archiv für das Eisenhüttenwesen, 1942, vol. 15, May, pp. 479–490. (*See* Journ. I. and S.I., 1945, No. II., p. 184 A.)

The Origin of Silicate Inclusions in Basic Arc Furnace Steel with High Carbon Contents. A. Hultgren. (Jernkontorets Annaler, 1945, vol. 129, No. 11, pp. 633–671). (In Swedish). The occurrence of silicate inclusions in two types of steel made in a basic-lined furnace was investigated; one steel contained 1·10% of carbon and the other was a spring steel containing 0·65% of carbon, 0·70% of silicon and 1·0% of manganese. The object was to determine the conditions promoting the formation of silicate inclusions during tapping and pouring, the effect of the time the steel was kept in the ladle, and the value of certain measures for diminishing the inclusions. With the metallurgical practice followed, the steel was practically free from inclusions and low in oxygen when tapped from the furnace, but in the ladle, immediately after tapping, it contained spherical drops of silicate in greater quantity the more turbulent the tapping stream, the proportion present varying between $1{\cdot}4 \times 10^{-3}$ and 41×10^{-3} volume-%. The oxygen content also rose during tapping; contrary to expectation, the increase was less in the case of a turbulent stream. It is suggested that the intimate mixture of the white furnace slag may have caused some deoxidation of the steel; this is known as the "Perrin effect." Keeping the steel in the ladle for a few minutes caused the greater part of the silicates to disappear. For instance, the quantity was reduced from 12×10^{-3} to $1{\cdot}2 \times 10^{-3}$ volume-% in 4 min. In the same period the average diameter of the inclusions greater than 0·010 mm. decreased from 0·031–0·108 to 0·022–0·041 mm., and their structure also altered; when just formed they were mainly crystalline, whilst after a few minutes they were more or less glassy. It may be assumed that the oxidation of the tapping stream results in the formation of a silicate relatively rich in iron and manganese oxides. This will gradually dissolve in the unsaturated liquid steel and, by reaction with the silicon in the steel, the latter will become poorer in these oxides and richer in silica. At the same time the greater part of the larger inclusions will disappear from the steel by rising to the surface. Some 2-in. ingots were cast from the ladle using normal and restricted streams; the restriction caused an enormous increase in the inclusions. Evidence of the reactions between the inclusions and the steel was retained by the rapid freezing of the steel immediately after the formation of the inclusions which appeared as swarms of small drops around the larger ones. With ordinary 9 to 14-in. square ingots cast from the ladle, the silicate inclusions amounted to $0{\cdot}1 \times 10^{-3}$ to $0{\cdot}9 \times 10^{-3}$ volume-% (generally less than $0{\cdot}5 \times 10^{-3}$). Restricting the pouring stream or blowing air on to it had no appreciable effect on the quantity of inclusions, presumably because the silicate drops which did form had time to escape by rising. The last ingot to be poured was liable to contain a large number of silicate inclusions. When a Caspersson ladle was attached to the furnace and the steel was protected by an atmosphere of purified nitrogen, the silicate inclusions in the ingots were as low as $0{\cdot}02 \times 10^{-3}$ volume-%. The growth of the inclusions before the steel freezes in the mould is thought to be due to precipitation from solution and to diffusion in the liquid steel, and not to the coalescence of small drops.

FORGING, STAMPING, AND DRAWING

(Continued from pp. 22 A–23 A)

Electric-Pneumatic Hammers and Steam or Compressed Air Hammers, with Particular Reference to Their Economy. F. Knorr. (Stahl und Eisen, 1943, vol. 63, June 3, pp. 433–437; June 10, pp. 456–462). Modern electric-pneumatic hammers and steam hammers are described. The factors affecting their efficiency and data on the energy consumption of different hammers on similar production operations are presented and discussed.

Forging Die Design. J. Mueller. (Steel Processing, 1945, vol. 31, Nov., pp. 696–698). Some of the principles applied in the design of cushioned helve-

hammers and multiple dies for forging shafting are discussed.

Processing and Fabrication of Stainless Steel Sheet and Plate Products. H. S. Schaufus and W. H. Braun. (Steel Processing, 1945, vol. 31, Oct., pp. 625–629; Nov., pp. 691–694). In the first of this series of articles the composition, structure and properties of the stainless steels are dealt with, and in the second part the annealing, stabilizing and stress-relieving are discussed with micrographs of the structures obtained.

Drawing Stainless Cylinders. L. E. Browne. (Steel, 1945, vol. 117, Dec. 10, pp. 116, 117, 170). Inner cylinders which serve as vacuum chambers for water-cooled ignition tubes of stainless steel have been successfully drawn with the two ends of greater diameter than the centre, the final dimensions being accurate within 0·010 in. Details of the drawing process are given.

Cold Metal Contour Forming. R. A. MacKenzie. (Steel, 1945, vol. 117, Dec. 10, pp. 112–113, 164–166). Machines for stretch-forming and contour-forming sheet metal into a wide variety of complicated shapes are described. These machines do not require such expensive dies as do hydraulic presses.

Elastic Properties of Steel Wire Intended for Springs and Formed Parts. N. C. Talmadge. (Wire and Wire Products, 1945, vol. 20, Nov., pp. 859–861, 884). It was found that a cold-drawn wire was suitable for coiling into springs when the yield point was between 56% and 75% of the tensile strength; with higher yield-point ratios the wire was unsuitable. The effect of straightening and tempering at different temperatures on the tensile strength, yield point, and elongation of hard-drawn steel wires 0·092, 0·100, and 0·120 in. in dia. is discussed and test data are presented.

Reactive Wire Drawing. II. Janet M. Howden and R. W. Lunt. (Wire Industry, 1945, vol. 12, Dec., pp. 641–645). The available data for reactive wire-drawing are examined to derive values for the coefficient of friction between the wire and the die, the mean pressure between the wire and the die, and a factor which is likely to determine the increase in die life which is obtained by replacing non-reactive by reactive drawing.

A Chronology of Wire and Wire Products. F. R. Morral. (Wire and Wire Products, 1945, vol. 20, Nov., pp. 862–866, 885–887). A very comprehensive chronology of the history of the development of wire making from the discovery of copper up to 1942 is presented. The chronology is the result of research work using French, German, English and American publications, and it is claimed that a complete search of all books, patents, and journals in different languages was made.

HEAT-TREATMENT

(Continued from pp. 24 A–26 A)

Neutral Salt Bath Hardening. L. F. Train. (American Society for Metals: Canadian Metals and Metallurgical Industries, 1945, vol. 8, Nov., pp. 31, 48). A description is given of a set of four electrically heated salt-bath furnaces for heat-treating tools. The four furnaces are for preheating to 1200–1750° F., bringing up to the hardening temperature in the 1750–2350° F. range, quenching in molten salt at 1200–1250° F., and tempering at 400–1100° F., respectively.

Manufacture of File Hard Precision Gears. W. G. Guthrie. (Metal Progress, 1945, vol. 48, Dec., pp. 1300–1305). A description is given of one of the General Motors Corporation plants for the heat-treatment of gears of 3·5%-nickel, 1·5%-chromium steel. The carburizing is carried out in " Homo-Carb " atmosphere-controlled furnaces.

Modern Heat Treatment of Steel. A. C. Macdonald. (Journal of the Institution of Production Engineers, 1946, vol. 25, Jan., pp. 1–28). A comprehensive account of the theory of heat-treatment is presented. Definitions of terms are given, the effects of alloying elements are explained, and descriptions are given of the Jominy end-quench test, refrigeration treatment, and induction hardening.

Modern Heat Treatment of Ferrous Materials. J. R. Mott. (American Society for Metals: Canadian Metals and Metallurgical Industries, 1945, vol. 8, Nov., pp. 26–28). The preparation of atmospheres for carburizing steel is discussed and methods of determining whether the surface of steel has been carburized or decarburized are described.

Surface Hardening. Possibilities of its Application to Castings. M. B. de Jessey. (Iron and Steel, 1945, vol. 18, Dec., pp. 667–669). This is a translation of an article published in " Bulletin de l'Association Technique de Fonderie," dealing with the surface hardening of iron castings. The process consists of raising a part of the metal locally to the hardening temperature and quenching it, the structure and constitution of the rest of the casting remaining unchanged. Two methods of heating are in use: *viz.* by induction and by blowpipe. The hardening technique is fully described.

The Development of Induction Furnaces and Physical Laws. L. Dreyfus. (Teknisk Tidskrift, 1946, vol. 76, Feb. 2, pp. 113–123). (In Swedish). The theory governing the design of high-frequency induction furnaces is critically discussed with special reference to furnaces for hardening and tempering rock-boring bits and gear teeth, examples of which are described.

Induction Heating. J. S. Edgar. (American Society for Metals: Canadian Metals and Metallurgical Industries, 1945, vol. 8, Nov., pp. 28–30). Several examples of the application of induction hardening are described.

High-Frequency Heating. (Automobile Engineer, 1946, vol. 36, Jan., pp. 13–19). The basic principles of induction heating, the fields of application, and efficiencies are outlined. The three types of equipment, motor-generator, spark-gap converter, and thermionic oscillator are discussed. Special-purpose machines for through-heating, surface hardening,

semi-continuous operation, and localized heating are described in detail.

Effects of Various Surface and Structural Conditions on Nitriding. R. W. Allott. (Machine Shop Magazine, 1945, vol. 6, Dec., pp. 90–92). The author disagrees with the conclusions drawn by F. F. Dodson (*see* Journ. I. and S.I., 1945, No. II., p. 139 A) relating to the causes of defects in nitrided cases. Experiments are described which support the view that defects in nitrided cases are not necessarily due to the presence of grease or oxide films.

Some Aspects of the Overheating of Steel Drop-Forgings. H. J. Merchant. (Iron and Steel Institute, 1946, this Journal, Section I.). The effects of overheating on the serviceability of steel drop-forgings, particularly in relation to their use in aero-engine construction, are discussed. The principal causes of, and factors influencing, overheating are described, and an attempt is made to differentiate between overheated steel, severely overheated steel, and burnt steel. The greater part of the paper is devoted to a description of the methods used to detect overheating in alloy steel, namely, examination of the surface and of the fracture, metallographic examination, and mechanical testing. Work carried out with a view to studying obscure aspects of the subject, together with an attempt to establish fracture-test standards, is described. An account is given of methods of preventing overheating and of reclaiming overheated steel. Finally, there are some notes on the occurrence of overheating in American steels, and some suggestions are given regarding directions which might be taken by future research on this subject.

The Overheating and Burning of Steel. A. Preece, A. Hartley, S. E. Mayer, and J. Nutting. (Iron and Steel Institute, 1946, this Journal, Section I.). The overheating properties of a wide variety of steels have been examined. The temperatures of overheating have been determined on the basis of the fracture and etch tests, a critical examination of these tests showing them to be satisfactory for this purpose.

There would appear to be no clear relationship between the overheating temperature and the normal specified analysis of the steel, or its oxygen and nitrogen contents. Open-hearth steels have generally a higher overheating temperature than electric steels. An unexpected correlation has been observed between the inclusion content of a steel and its overheating temperature.

Furnace conditions, such as composition of the atmosphere, soaking time, and the rate of cooling, have been studied in relation to overheating. From this, the possibility of a slow cooling treatment as an effective method of restoring overheated steels has been indicated. The effect of overheating upon the tensile and Izod properties has also been examined.

Results obtained in this investigation provide further information on the mechanism of overheating.

The Effect of Oxygen on the Isothermal Transformations of Steel, and a Suggested Test for Burning. F. C. Thompson and L. R. Stanton. (Iron and Steel Institute, 1946, this Journal, Section I.). Samples of a series of plain carbon steel have been locally burned, and subsequently isothermally quenched to various temperatures, with a view to finding a test for burned material.

The results show that certain steels are rendered more reactive by burning, and this suggests a displacement of the inherent S-curve; the nature of the final product of transformation indicates that this displacement is in a vertical direction, which in effect acts as a shift to the left.

The deduction is made that this behaviour is due to the introduction of oxygen during burning, which probably acts indirectly.

The effect is absent in other steels of similar composition, as determined by ordinary methods of analysis, and in general it is found to be too erratic to offer a universal test for burning.

Overheating and Burning of Nickel-Chromium-Molybdenum Steel. W. E. Goodrich. (Iron and Steel Institute, 1946, this Journal, Section I.). Occasionally, fractured test-pieces removed from forgings for routine inspection have disclosed small areas of granular facets, which some inspectors have interpreted as indicative of "burnt" steel. More conservative opinion, however, has regarded these areas as possible signs of "overheating," and that the evidence of such a condition might be masked by slow rates of cooling while, on the other hand, signs of overheating, as judged by fractures, may occur in material which has not, in fact, been overheated. A series of experiments were therefore conducted on sections machined from a nickel–chromium–molybdenum–vanadium steel forging, the sections being heated to initial temperatures varying between 1250° and 1400° C. and, afterwards, subjected to various cooling treatments, in some cases followed by a further standard oil-hardening and tempering operation. Afterwards, the specimens were fractured and their fractures and metallographic structures, in the various heat-treated conditions, are described.

It has been shown that a repetition of normal oil-hardening and tempering treatments, or slow cooling from overheating temperatures, can appreciably reduce, and in many cases entirely eliminate, the abnormal granular type of fracture. All the evidence obtained indicated that it was necessary to cool fairly rapidly through the upper critical range to create conditions favourable for the formation of the granular facets, and even then tempering temperatures exceeding approximately 400° C. were necessary to produce the relative strengths of the crystals and crystal boundaries required for their formation.

Even at overheating temperatures of the order of 1400° C., no incipient fusion was detected at the grain boundaries or within the grains, though there were signs of a metallographic change apparently taking place in the solid state at the grain boundaries and also originating from non-metallic nuclei within the grains.

Some Experiments on Overheating. J. Woolman and H. W. Kirkby. (Iron and Steel Institute, 1946, this Journal, Section I.). A series of experiments has been carried out which were designed to throw light on the phenomenon of overheating and the

factors affecting it. Some evidence is submitted in support of a hypothesis that the overheating phenomenon indicated by facet fractures is a precipitation effect and is not the result of external gas atmospheres. It is considered that the precipitate is already present in the steel as cast, and the effect of heating to a high temperature is to redissolve it. Subsequent cooling, if at a suitable rate, results in a precipitate forming at the existing austenite boundaries which then persist as a network. This is reflected in the final fracture test by interruptions in the final path of the crack, giving rise to the facet type of fracture. The indications are that the rate of cooling from the overheating temperature is an important factor in producing facet fractures. The method of steelmaking and the addition of aluminium and other killing agents also have an influence on the minimum overheating temperature, although the reasons for both effects are not yet clear. The vacuum-melting experiments have also shown that a material having a very high overheating temperature can be substantially reduced by remelting, although the variables due to changes in composition introduce complexities. Besides oxygen, the sulphur contents appear to play an important rôle in the phenomenon.

WELDING AND CUTTING

(Continued from pp. 26 A–27 A)

An Analytical Examination of Weld Deposits from Commercial Mild Steel Electrodes to Specification B.S.S. 639A, and the Manufacture of Artificial Weld Metal. G. L. Hopkin. (British Welding Research Association, Symposium on Metallurgy of Steel Welding, Nov., 1945). A series of deposits from twenty commercial mild steel electrodes have been examined analytically. Large variations were found in the nitrogen contents of samples taken from top and bottom of deposits made with 12 S.W.G. electrodes, but the differences decreased as the electrode size increased and in 50% of the 4 S.W.G. electrodes the bottom of the deposit showed a higher content than the top. Large variations in silicon content were found between the different gauges, the 12 S.W.G. electrodes invariably containing the highest content. To study the effect of nitrogen on the mechanical properties of cast steel of weld-metal composition, attempts were made to manufacture an artificial weld metal high in nitrogen. It was found, however, that exceedingly long annealing times would be required in order to obtain diffusion of the nitrogen to the centre of the specimens; this investigation was therefore discontinued.

Comments on the Rôle of Hydrogen in Relation to the Cracking of Alloy Steels on Welding. G. L. Hopkin. (British Welding Research Association, Symposium on Metallurgy of Steel Welding, Nov., 1945). The theories put forward to explain why the heat-affected zones of parent plate vary in their apparent brittleness when different welding electrodes are used are discussed. The main factor, according to the author's theory, is the quantity of hydrogen which diffuses into the somewhat brittle and stressed heat-affected zones during cooling and when cold. Tests have shown that the killed ferritic deposits evolve two to three times the volume of hydrogen in the cold which is evolved by specially made low-hydrogen electrodes, and that these, in turn, evolve about two to three times the hydrogen given off from the "oxidised" deposits. Little or no gas is evolved from the austenitic deposits.

The Effect of Initial Heating Temperature on the Mechanical Properties of an Air-Hardened Ni–Cr–Mo Steel. J. A. Wheeler and V. Kondic. (British Welding Research Association, Symposium on Metallurgy of Steel Welding, Nov., 1945). A report is presented of an investigation of the effect of the temperature to which an air-hardening steel is heated before quenching, on the mechanical properties of the martensite which is formed. The temperature range covered was 850–1475° C., which includes almost the whole range of heat-treatment temperatures characteristic of the hardened zone of a weld. The steel used contained 3·38% of nickel, 0·65% of chromium, and 0·26% of molybdenum. There was evidence of a slight abnormality in the region of 1350° C. as there was a drop in the hardness and tensile strength after initial treatment at this temperature.

Electro-Physics of the Welding Arc. L. H. Orton. (British Welding Research Association, Symposium on Metallurgy of Welding, Nov., 1945). Work already done on the physics of the welding arc is reviewed and the programme of work to be carried out by the Committee on "The Electro-Physics of the Arc" is outlined.

Cracking of Welded Gas Mains. L. Reeve. (British Welding Research Association, Symposium on Metallurgy of Welding, Nov., 1945). The causes of failure of welded gas mains by cracks appearing near butt and fillet welds are being investigated. Similar cracks have been developed in welded steel plate immersed in boiling solutions of ammonium, calcium, and sodium nitrate in as short a period as 16 hr., and the following tentative conclusions have been arrived at: (1) A minimum degree of stress, which varies with the type of steel used, must be present to produce failure; the most sensitive steels will fail at an imposed stress of less than 4 tons per sq. in. in the absence of plastic strain. (2) With severe plastic strain, failure will occur within 10 days with all the types of steel that have been tested. (3) Failure can be prevented by stress-relieving treatment.

An Apparatus for the Determination of the Viscosity of Welding Slags. P. K. Gledhill. (British Welding Research Association, Symposium on Metallurgy of Steel Welding, Nov., 1945). A description is given of a modified Herty-type viscometer with which rapid determinations of the viscosity of welding slags can be made.

Statement on Weldability Tests for Specification Purposes. H. O'Neill. (British Welding Research Association, Symposium on Metallurgy of Steel Welding, Nov., 1945). A brief survey is made of the work done by Committee FM.2 of the British Welding Research Association which is studying weldability

tests. All known tests have been reviewed, but only the following are receiving further consideration : (*a*) The tube triangle test ; (*b*) the circular patch test ; (*c*) the Reeve fillet test ; and (*d*) the rigid butt joint test.

The Flash Welding of Steel. J. C. Barrett. (Iron and Steel Engineer, 1945, vol. 22, Dec., pp. 103–113). The principles of flash-welding are discussed and their applications to modern production problems are described. Many illustrations of machines for flash-butt-welding bars up to $1\frac{3}{4}$ in. in dia., aircraft landing gear assemblies, and crankshaft counterweights are reproduced.

Production Technique and Quality of Flash-Welded Joints. H. Kilger. (Welding Journal, 1945, vol. 24, Aug., pp. 413-S–432-S ; Oct., pp. 506-S–520-S). An English translation is presented of sections of Part II. of Dr. Hans Kilger's book " *Fertigungstechnik und Güte abbrenngeschweisster Verbindungen* " which was published in 1936. Although the work is limited to manually operated machines and to the simpler commercial carbon steels, the author has considered, and to some extent solved, many of the problems confronting the welding industry.

Observations on the Appearance Welding of Malleable Castings. H. A. Schwartz, I. Young, and J. Hedberg. (American Society for Testing Materials, 1945, Preprint No. 31). The repair of malleable iron castings by welding is discussed with special reference to the microstructure which is to be expected after employing different welding techniques. It is considered that, with a short heat-treatment after welding, a machinable repair can be effected.

The Distortion of Steel Joists Welded on One Flange. R. Malisius. (Zeitschrift des Vereines deutscher Ingenieure, 1940, vol. 84, Sept. 7, pp. 661–662). Accurate measurements were made of the distortion of flat steel bars and joists caused by the deposition of weld metal along one edge or flange. The effects of different thickness and width of the parent metal on the hogging and sagging during and after welding was studied.

Straining of Weld Metal during Cooling. E. P. De Garmo. (Iron Age, 1945, vol. 156, Dec. 20, pp. 48–50). Failures have occurred in welded joints where the weld metal is deposited on plates offering a high degree of restraint, and in these cases the weld metal exhibited no ductility. Specimens were cut from different positions along a butt weld 2 ft. long joining two large plates 1 in. thick. Those from the ends of the weld, which had not been plastically strained during cooling, were given known amounts of plastic strain. Tensile tests were then made on all the specimens and the yield points, maximum and ultimate loads and total elongations were very accurately determined. A comparison of the results revealed that the metal half-way along the weld had been strained plastically by an amount equivalent to a stress higher than the yield point.

Effect of Three Variables in Spot-Welding. H. Van Sciver. (Metal Progress, 1945, vol. 48, Dec., pp. 1292–1295). The strength and structure of spot welds in 18/8 stainless steel sheet 0·075 in. thick was investigated by series of tests in which three of the four conditions, viz., current, time, tip pressure, and electrode shape, were kept constant and the fourth was varied. The results are indicated by a series of 32 photographs of sections through the welds.

Weldability. A. Leroy. (Revue de Métallurgie, Mémoires, 1944, vol. 41, Jan., pp. 26–32). A short review is presented of welding methods and tests, and factors influencing the weldability of metals are discussed.

Weldability Factors for 18-8 Stainless. F. H. Page, jun. (Iron Age, 1945, vol. 156, Dec. 27, pp. 58–61). Different heats of stabilized 18/8 stainless steel are known to show wide differences in weldability even when their chemical composition complies with official specifications. The effects of slight variations in the percentages of silicon, manganese, and other elements on the weldability are discussed.

The Fatigue Strength and Notch Sensitivity of Electric-Arc Weld Metal. C. Schaub. (Teknisk Tidskrift, 1945, vol. 75, Nov. 17, pp. 1263–1266). (In Swedish). The results of rotating bend-fatigue tests on specimens of weld metal machined with different radii at the shoulder are presented and discussed. These show that the notch sensitivity of weld metal is greater than is generally believed.

The Production and Repair of High-Speed Steel Tools by Welding. R. Gunnert. (Teknisk Tidskrift, 1946, vol. 76, Jan. 19, pp. 57–64). (In Swedish). A comprehensive account is given of the production, heat-treatment, and repair of high-speed steel tools and milling cutters by the deposition of tungsten-steel weld metal. The influence of different heat-treatments on tool life is discussed.

The Cold-Welding of Cast Iron. P. Krug. (Zeitschrift des Vereines deutscher Ingenieure, 1940, vol. 84, Oct. 12, pp. 777–783). Hardness and tensile tests were carried out on electric-welded joints in five different cast irons. The joints were cold-welded (*i.e.*, without preheating) and the effect of spraying the joint faces with aluminium, lead, zinc, nickel, and copper was studied. Coating with copper greatly improved the quality of the welds obtained in irons with poor welding properties. More than 1% of phosphorus in the cast iron has a detrimental effect on the weldability.

Repair of Rolling-Mill Pinion by Thermit Welding. (Engineering, 1946, vol. 161, Jan. 11, pp. 32–33). An account is given of the technique employed for the repair by thermit welding of a broken pinion shaft for a rolling mill. The broken portion of the 27-in. dia. shaft was parted off and a new length of shaft $27\frac{1}{4}$ in. in dia. was successfully welded on by the thermit process.

Aluminium Bronze Welding in Steel Plant Maintenance. F. E. Garriott. (Iron and Steel Engineer, 1945, vol. 22, Dec., pp. 98–102). The application of aluminium-bronzes (*i.e.*, copper alloys containing 5–14% of aluminium and up to 5% of iron) in steel mills for repairing equipment subject to wear and corrosive attack is discussed and the mechanical properties of the alloys detailed. Their application in the form of coated electrodes for metallic-arc, carbon-arc, and oxy-acetylene welding to make joints of high strength for maintenance work is dealt with.

Production Brazing Developments. (Machinery, 1946, vol. 68, Jan. 17, pp. 77–84). After a historical review of brazing and soldering methods the modern technique is described and illustrated, and the post-war possibilities in production discussed. Various applications are described, among them the fabrication and repair of tools. Whilst the older methods required skilled operators, the modern high-production methods tend to eliminate the human element by employing automatic or semi-automatic means of heating (*e.g.*, by induction). The silver-copper-cadmium-zinc alloy is mainly used in the form of wire, rod, or sheet in a wide variety of sizes. The importance of cleaning is emphasized.

New "Heenan" Plant; Chain Making Equipment. (Wire Industry, 1945, vol. 12, Dec., pp. 637–639). Modern machinery for forming and welding chains is described.

Powdered Metal Welding Rods. (Steel, 1945, vol. 117, Dec. 10, pp. 130, 133). A new process is described, which was developed for making electrodes for welding alloy steels by compacting powdered metals around an iron wire core.

Standardization in Welding. (Zeitschrift des Vereines deutscher Ingenieure, 1940, vol. 84, May 11, pp. 325–329). Particulars are given of the proposed German standard specifications for welding processes. Draughtsmen's symbols for welded joints, which are intended to bring up-to-date the DIN 1910/12 specifications issued in 1927, are also given.

Oxy-Acetylene Cutting. P. Krug. (Zeitschrift des Vereines deutscher Ingenieure, 1940, vol. 84, Sept. 21, pp. 713–716). Some German oxy-acetylene cutting machines are described and data on cutting speeds, consumption of oxygen and acetylene, and the effect of alloying elements on the cutting process are presented and discussed.

MACHINING

(Continued from p. 27 A)

Machinability. (Automobile Engineer, 1945, vol. 35, Dec., p. 553). A discussion of machinability, defined as the property of the material that affects the speed at which a given cut may be taken, and its importance in production economics, is presented. It is shown by machining experiments that the structure of the metal has a marked influence on the machinability of steel. The degree of machinability (in turning, forming, drilling, and broaching) of steels heat-treated in various ways is given in a table.

Machinability of Sulphurized Steels. H. M. Clarke. (Steel, 1946, vol. 117, Dec. 17, pp. 116–119, 162). Various processes of adding sulphur to steel to give it good machining properties have been patented. In this paper an addition in the form of an anhydrous sulphite is advocated. The results of machining tests on steels sulphurized by this method are presented and discussed.

The Measurement of Finely Finished Surfaces by Optical Interference. C. Timms. (Journal of Scientific Instruments, 1945, vol. 22, Dec., pp. 245–246). The author describes a method of measuring the depth and pitch of fine surface irregularities as produced by lapping or similar refined processes, by making use of optical interference. It is strictly limited to fine finishes where the surface irregularities do not exceed 0·00001 in. total depth. The method is self-calibrating since the separation of any two adjacent fringes automatically provides a scale of units each corresponding to half the wave-length of the light used.

Optical Methods of Examining the Quality of Surfaces. B. Frischmuth. (Schweizer Archiv, 1945, vol. 11, Sept., 262–269). Optical methods of evaluating metal surfaces are reviewed and a description is given of an instrument which, in conjunction with a metallographic microscope, enables evaluations to be made by the light-interference method.

CLEANING AND PICKLING OF METALS

(Continued from pp. 9 A–10 A)

Glycerine in Metal Treatment. G. Leffingwell and M. A. Lesser. (Engineering Materials and Processing Methods, 1945, vol. 22, Nov., pp. 1432–1434). The literature on the use of glycerine in solutions for cleaning metals is reviewed.

The Use of Steel Turnings as a Cleaning Medium Instead of Steel Grit. A. Kentischer. (Giesserei, 1944, vol. 31, July, pp. 101–106). Owing to the difficulty in obtaining steel grit for cleaning castings tests were made using cast-iron borings, chips from the planing of cast iron, and steel turnings. All three materials were found to be good substitutes. When steel turnings were broken up by tumbling with small castings in a revolving drum, the product had about the same particle size as the steel grit and it had a longer life when used for cleaning by the centrifugal method. A great saving was effected, as the broken steel turnings cost only 15% of the price of the steel grit.

Cleaning Castings by the Hydro-Blast System. (Machinery, 1945, vol. 67, Dec. 13, pp. 672–674). A detailed description is given of the equipment for cleaning castings by the Hydro-blast system in which a stream of water and sand at high pressure (1200 lb./sq. in.) is projected against the casting from a gun.

Electrolytic Methods of Polishing Metals. S. Wernick. (Sheet Metal Industries, 1945, vol. 22, July, pp. 1221–1222, 1229–1233; Sept., pp. 1586–1592; Nov., pp. 1951–1958). Conclusion of a series of

articles (*see* Journ. I. and S.I., 1945, No. II., p. 61 A). In Part VIII. the polishing of the precious metals is described. Part IX. is devoted to the polishing of rhodium. In Part X. the literature on the electrolytic polishing of carbon steels is reviewed.

Selection of Metal Cleaning Methods. C. D. Townsend. (Engineering Materials and Processing Methods, 1945, vol. 22, Nov., pp. 1411–1417). Petroleum solvents, emulsifiable cleaners, alkaline cleaners, vapour-degreasing, blast-cleaning and tumbling are discussed and the characteristics of each process are pointed out.

Vapor Degreasing. J. C. Joyce. (Steel, 1945, vol. 117, Nov. 26, pp. 110–116). Descriptions are given of modern electric and gas-heated degreasing plants employing perchlorethylene or trichlorethylene.

Sodium Hydride Descaling. L. W. Townsend. (Steel, 1945, vol. 117, Nov. 12, pp. 122–123, 180–184). A problem in the production of stainless clad steel was to obtain a white pickled stainless steel surface and at the same time prevent the over-pickling of the low-alloy backing steel. The bath prepared for this purpose consisted of molten caustic soda at 700° F. into which metallic sodium and hydrogen were introduced to form a solution of 2–3% sodium hydride. After hosing the steel with water at high pressure it is dipped for 2 min. in a 5–10% sulphuric acid bath followed by immersion for 2–3 min. in 10% nitric acid at 160° F.

Descaling Stainless Steel. (Steel, 1945, vol. 117, Nov. 19, pp. 121, 180–182). The application of the sodium-hydride descaling process (*see* preceding abstract) to the cleaning of coils of stainless steel wire is described and illustrated.

Sodium Hydride Process for Descaling Steel. J. Albin. (Iron Age, 1945, vol. 156, Nov. 8, pp. 58–63). The development of the plant and process for descaling alloy steels, and especially stainless steel, in a solution of sodium hydride and caustic soda is described (*see* preceding abstracts).

The Effects of Different Methods of Pretreating Iron and Steel before Painting. F. Fancutt. (Iron and Steel Institute, 1946, Special Report No. 31). The dependence of the durability of paint applied to iron and steel upon the surface condition is strongly emphasized by the results of this investigation. All treatments tested which leave the steel surface in a rust-free, scale-free condition at the time of paint application are comparable in presenting an " ideal " surface for painting, and the choice between them will generally be determined on economic grounds or convenience of operation.

The simultaneous presence of rust and scale below a paint film induces rapid breakdown, while light surface rust in the absence of scale, though accelerating paint failure, is not so deleterious, especially where red-lead paint is used in priming. Exposure of the descaled steel, unless accompanied by the formation of a visible film of rust, does not, however, shorten the life of paint subsequently applied.

The durability of paint applied to the as-rolled surface (*i.e.*, scale bearing, but rust-free), provided the film of scale is practically complete and unbroken, is much the same as for the scale-free, rust-free surface.

The rate of breakdown of paint applied to a clean, rust-free, scale-free surface appears to be mainly a function of the paint itself, and to be largely independent of (*a*) the type of steel, (*b*) the descaling method employed, *i.e.*, chemical or mechanical, (*c*) nature of acid used, (*d*) the presence or absence of inhibitors added to the pickling bath, and (*e*) the washing process employed after pickling.

The life of paint applied to a steel surface not in the ideal condition is, on the other hand, influenced by a number of factors, including (*a*) the type of steel, and (*b*) the nature of acid used, in addition to the sometimes overwhelming factor of surface condition.

The method of paint application is of importance when it influences the weight of paint applied, and in this investigation spray-applied films were heavier and consequently more durable than brushed ones. Red-lead priming is much superior to red oxide on rusty surfaces, but the difference is less, and may even be reversed under certain conditions, when rust-free, scale-free surfaces are involved.

Flame-Priming Steel Surfaces for Painting. R. J. Anderson. (Engineering Journal, 1945, vol. 28, Nov., pp. 707–712). The behaviour of rust and mill-scale on heating is discussed and the flame-priming (heating with a multiple-burner oxy-acetylene torch) of steel surfaces to prepare them for painting is described. A burner head 6 in. wide has 49 flame ports $\frac{1}{8}$ in. apart. If the burner is kept moving at 35 ft./min., about 13 cu. ft. each of oxygen and acetylene would be consumed for every 100 sq. ft. of surface.

A Mixed Acid Pickling and Recovery Installation Based on the De Lattre Process. E. W. Mulcahy. (Sheet Metal Industries, 1946, vol. 23, Jan., pp. 77–81). A description of the De Lattre pickling process has been given by A. McLeod (*see* Journ. I. and S.I., 1940, No. II., p. 189 A); since then two plants have been installed in Great Britain and a description of the larger one is given in this paper. Special advantages of the process are that the recovery method has reduced the acid consumption to a minimum; and the steam consumption also is low owing to the lower working temperatures required.

COATING OF METALS

(Continued from pp. 10 A–11 A)

Plating with Insoluble Anodes. W. R. Binai. (Metal Finishing, 1945, vol. 43, Apr., pp. 144–146, 147). The advantages and disadvantages of plating with insoluble anodes are discussed.

Electroplating Metal Sheets Prior to Fabrication. E. A. Ollard and E. B. Smith. (Sheet Metal Industries, 1946, vol. 23, Jan., pp. 116–126). Details are given of the production of electroplated steel strip for making pressings and stampings.

An Examination of Electroplating Processes for

Stainless Steels. H. Krause. (Korrosion und Metallschutz, 1940, vol. 16, Sept., pp. 304–308). Old and new methods of plating stainless steels are reviewed.

Hard Chromium Plating. J. J. Dale. (Monthly Review of the American Electroplaters' Society, 1945, vol. 32, June, pp. 581–594, 619). A general survey of the technique and use of hard chromium plating is presented. Operating characteristics of the baths, pretreatments for the metals to be plated, and practical advice to ensure good results are included.

The Application of Electrolytic Chromium as Protection Against Corrosion. K. Gebauer. (Korrosion und Metallschutz, 1940, vol. 16, Sept., pp. 297–299). Methods of plating chromium on iron and steel by electrolysis are discussed, with special reference to the conditions which prevent the formation of porous or cracked coatings.

Nickel Flashing and Its Relation to Enamel Adherence. E. Wainer and W. J. Baldwin. (Journal of the American Ceramic Society, 1945, vol. 28, Nov., pp. 317–326). The manner in which a flash coat of nickel improves the adherence of enamel on steel is discussed. The rôle of nickel in improving adherence is possibly bound up with retarded oxidation. Adherence may be considered as a corrosion phenomenon developed by the action of gases and other reagents. The degree of adherence is a function of the oxygen pressure at the interface when the glass is fused. The equilibria developed are strongly affected by the presence of nickel. Using coatings directly on iron, the amount of nickel required varies with each particular enamel composition. Some evidence regarding the nature of the oxide that promotes adherence is presented.

The Technique of Sheet Galvanising by the Hot Dip Process. H. Edwards. (Sheet Metal Industries, 1945, vol. 22, Oct., pp. 1725–1730, 1736; Nov., pp. 1914–1922; Dec., pp. 2096–2103, 2108). Conclusion of a series of articles on the hot-dip galvanizing process as practised at the works of John Summers and Sons, Ltd. (*See* Journ. I. and S. I., 1945, No. II., p. 166 A.

Specification Zinc Plating on Steel Sheets. W. H. Safranek. (Monthly Review of the American Electroplaters' Society, 1945, vol. 32, June, pp. 567–578). The conditions which are essential for good zinc-plating on steel sheet for assemblies requiring fairly high tensile strength without reduction in ductility and corrosion resistance, are discussed. A number of graphs and tables correlate the effects of various chemicals, temperature, current density, and dilution with efficiency and throwing power.

Current Zinc Electroplating Practice. A. G. Gray. (Steel, 1945, vol. 117, Oct. 8, pp. 109, 158–170; Oct. 15, pp. 136–142; Oct. 22, pp. 129–134; Oct. 29, pp. 110–114, 146; Nov. 5, pp. 142–144, 182–186; Nov. 12, pp. 132–136). Detailed descriptions of electrolytic methods of depositing zinc on steel are given; the merits and limitations of acid and of cyanide baths are discussed with data on these methods as well as on the zinc-mercury process. The testing and properties of the coatings are also dealt with.

The Cronak Process as Applied to Zinc Plate. S. E. Maxon. (Metal Finishing, 1945, vol. 43, Apr., pp. 148–149). A method of increasing the corrosion resistance of zinc coatings is described. It is called the Cronak process, and consists of cleaning the zinc surface and dipping in a sodium-dichromate–sulphuric-acid solution.

Developments in Tin and Tin Alloy Coatings. E. S. Hedges. (Chemistry and Industry, 1945, Dec. 1, pp. 370–372). Some results of recent work at the Tin Research Institute are reviewed. The most important single factor in obtaining high quality tin coatings is the preparation of the steel base. Provided that rigorous precautions in the preparation are taken, acid-stannous-sulphate baths produce the best quality coatings; the alkaline bath deposits are considerably less sensitive to the pretreatment. Two methods of tinning cast iron are briefly described.

The Tinning of Cast Iron. R. A. Cresswell. (Journal of the Iron and Steel Institute, 1945, No. II., pp. 157 P–169 P). The quality of hot-dipped tin coatings on cast iron after different pretreatments is investigated, using the criteria of continuity of coating, rust resistance, and adhesion. The nature of the bond between tin and cast iron is also studied by microscopical examination.

The poor tinning quality of cast iron is shown to be caused mainly by the presence of graphite flakes and to be intensified by contamination of the iron surface by graphitic sludge after pickling in acids. Investigation of modifications of the ordinary tinning processes shows that improved tin coatings can be obtained by reducing the duration of pickling in acids to a minimum; this is facilitated by good mechanical cleaning. The best pickling agent is found to be a cold mixture containing 5 vol.-% sulphuric acid and 5 vol.-% hydrofluoric acid. The corrosion resistance and adhesion of coatings obtained by such modifications of ordinary methods are, however, still low.

Two new methods of preparing cast iron for tinning are described, both involving treatment in molten salts. The chloride method consists of immersing the article in the fused zinc-chloride–sodium-chloride eutectic mixture at 300–350° C., followed by dipping in tin covered with a layer of the same fused salt mixture, at 300° C. This method gives adherent protective coatings of tin on cast iron which has been well cleaned mechanically. When the cast iron is bonded to white metal, consistent adhesion values of from 2 to 2·8 tons/sq. in. are obtained. The chloride method can be adapted to tinning by wiping.

The nitrate method was developed to give highly adherent coatings of tin and involves the following steps: light pickling in acid to "open up" graphite flakes; immersion for 15 min. at 300–350° C. in fused sodium-nitrate–potassium-nitrate eutectic mixture in order to oxidise surface graphite; pickling in dilute hydrofluoric acid to remove the scale formed in the nitrate bath; fluxing and tinning. Adhesion values of up to 3·8 tons/sq. in. are obtained between tin-base bearing alloy and cast iron tinned by this method. Microscopical examination of the bond shows that the tin penetrates cavities formerly occupied by graphite.

Electrodeposition of Iron-Tungsten Alloys from an Acid Plating Bath. M. L. Holt and R. E. Black. (Electrochemical Society: Metal Finishing, 1945, vol.

43, Apr., pp. 150–153, 176). A report is presented on the possibilities of electrodepositing tungsten alloys from commercial plating baths which are modified by an addition of sodium tungstate.

Metallizing as a Production Process. (Iron Age, 1945, vol. 156, Dec. 13, pp. 72–73). The utilization of the metallizing process in production methods is outlined and a description of the latest type metal-spraying gun is given.

Flame Spraying. W. D. Jones. (Metal Industry, 1946, vol. 68, Jan. 25, pp. 63–65). The process of protecting iron and steel surfaces by spraying metal powder with the Schori pistol is described. The advantages of this type of flame pistol are listed, and the application of zinc and aluminium for corrosion protection is outlined. One great advantage of the gun is its ability to apply a wide variety of non-metallic materials. The difference between flame-spraying and air-spraying is that in the former case one can dispense with solvents and drying, and thick coatings can be produceed in one application.

Corrosion Protection by Phosphatization—A Review. M. A. Streicher. (Corrosion, 1945, vol. 1, Dec., pp. 219–227). This review covers the chemistry of phosphatization, the properties of the solution and the phosphate coating, and industrial applications of the process. There are 43 references.

Physical Properties of Sprayed Metals. A. P. Shepard. (Metco News: Welding Journal, 1945, vol. 24, Oct., pp. 937–938). The structure of sprayed metal coatings is discussed, and data on the specific gravity of a number of sprayed coatings of ferrous and non-ferrous alloys are presented and compared with that of the wire used in each case.

Nomograph on Thicknesses of Electrodeposits. A. S. Covert. (Metal Finishing, 1945, vol. 43, Apr., p. 147). A nomograph is presented which enables a rapid determination to be made of the plating time necessary to produce a given thickness when the metal and the current density are known.

End Point Indication of the B.N.F. Jet Test for Measurement of Thickness of Zinc Coatings on Steel. S. G. Clarke. (Journal of The Electroplaters' Technical Society, 1945, vol. 20, p. 75). Particulars are given of a potassium ferricyanide solution which gives a clear indication of the perforation in the British Non-Ferrous Metals Research Association test for measuring the thickness of zinc coatings on steel.

The Surface Treatment of Hot-Dip Galvanised Coatings Preparatory to Painting and Its Relation to Corrosion Resistance. E. F. Pellowe and F. F. Pollak. (Sheet Metal Industries, 1946, vol. 23, Jan., pp. 82–85). Methods of improving the adhesion of paint coatings on galvanized steel are discussed; these include natural weathering, mechanical roughening, etching, and phosphatizing.

PROPERTIES AND TESTS

(Continued from pp. 27 A–31 A)

Developments in Ferrous Metallurgy. C. Sykes. (Institution of Civil Engineers, James Forrest Lecture: Metal Treatment, 1945, vol. 12, Winter Issue, pp. 245–258). The more outstanding developments of the last twenty years in the production of steel and in the knowledge of transformations, heat-treatment, welding, corrosion, scaling resistance and high-temperature properties are reviewed.

Metallic Materials Inspection with Particular Reference to Non-Destructive Testing Methods. J. E. Garside. (Manchester Association of Engineers, Nov., 1945, Advance Copy). A comprehensive survey is made of non-destructive methods of testing metals with special reference to those requiring neither expensive equipment nor highly-trained operators.

Non-Destructive Testing of Steel Castings. (American Foundryman, 1945, vol. 8, Nov., pp. 35–36). Methods and progress in setting up standards for the non-destructive testing of steel castings are reported. A bibliography of 20 recent publications is appended.

Contribution to a Study of the Influence of Austenite on the Mechanical, Physical and Technical Properties of Carbon Steels. G. Delbart and R. Potaszkin. (Revue de Métallurgie, Mémoires, 1944, vol. 41, Apr., pp. 97–110; May, pp. 143–149). A detailed investigation has been made of soft and medium carbon steels, prepared in the Héroult electric furnace. Data are given of the melting process and deoxidation, the latter being effected by different aluminium additions for each cast. The McQuaid-Ehn test was used for the grain-size determination. Test-pieces for the mechanical testing were taken from 30-mm. bars forged from 500-kg. ingots. The influence of the grain size of the austenite on the mechanical properties of soft carbon steel after annealing, case-hardening and quenching, and of medium-carbon steel after annealing and thermal refinement is discussed. The effect which the austenitic grain size has on the transformation points and on the ability of steel to undergo plastic deformation was also investigated.

The Effect of Combined Stresses on the Mechanical Properties of Steels between Room Temperature and −188° C. D. J. McAdam, jun., G. W. Geil, and R. W. Mebs. (American Society for Testing Materials, 1945, Preprint No. 22). Tensile tests were made on un-notched and notched specimens of carbon steels and alloy steels at several selected temperatures between room temperature and that of liquid air (−188° C.). The results are compared with those obtained with some non-ferrous metals. Results are presented in 17 diagrams which reveal the influence of combined stresses and stress concentration on the mechanical properties at various temperatures. Additional diagrams show the quantitative variation of these properties with temperature. The accelerated increase in the yield stress and the decrease in the ductility of iron and steels with decrease of temperature are anomalous. A "normal" metal shows not more than 75% increase of yield stress and no decrease of ductility with decrease from room temperature to −188° C.

X-Ray Stress Measurements on Unalloyed Steel When the Yield Point in Compression Is Exceeded. F. Bollenrath and E. Osswald. (Zeitschrift des Vereines deutscher Ingenieure, 1940, vol. 84, July 27, pp. 539–541). It was found by means of X-ray stress determinations that a state of internal stress existed in steel specimens subjected to compressive stresses exceeding the yield point, irrespective of the stress distribution in the elastic state. The internal stresses were concentrated at the core of the specimens. Earlier investigations have shown that the same occurs in tension, but that they are then concentrated at and near the surface.

Cromol Crankshafts. (Automobile Engineer, 1945, vol. 35, Dec., pp. 537–541). The design and advantages of crankshafts made from alloy cast-iron are described. Details are given of the chemical composition and the mechanical properties of Cromol, an alloy cast-iron specially developed for crankshafts. The metal structure that is desirable is described, and some of the important design factors are discussed.

The Effect of the Matrix Structure and Graphite Inclusions on the Properties of Cast Iron. G. Meyersberg. (Iron and Steel Institute, 1946, Translation Series, No. 260). An English translation is presented of a paper which appeared in Teknisk Tidskrift, 1945, vol. 75, June 9, pp. 641–654 (*see* Journ. I. and S.I., 1945, No. II., p. 119 A).

Raised Yield Strength in Bend Tests. G. Brewer. (Metal Progress, 1945, vol. 48, Dec., pp. 1306–1310). It is not generally known that when a solid round or square bar is tested in bending, the stress in the outside fibre may reach a value 40–65% above the limit of proportionality in tension before the bar suffers any permanent set. This is referred to as the "raised yield in bending." To obtain quantitative data on this raised yield strength an investigation was conducted with $2\frac{1}{2}$-in. round bars of a low-alloy chromium-nickel-molybdenum steel, as well as with chromium-molybdenum steel tubes by subjecting them to a pure bending moment and recording the strains by wire-type electrical strain gauges. An account of this investigation is given.

Strain Gage Technique. L. M. Ball. (Proceedings of the Society for Experimental Stress Analysis, 1945, vol. 3, No. 1, pp. 1–20). The practical details of the selection, design, and use of strain gauges are discussed.

Photoelasticity as a Designer's Tool. R. E. Orton. (Proceedings of the Society for Experimental Stress Analysis, 1945, vol. 3, No. 1, pp. 32–39). Examples of the application of photo-elastic stress analysis are described which dispel the impression that this method of investigation involves very expensive equipment and highly trained specialists to operate it.

The Use of a Plastic Model in Crankshaft Analysis. D. M. Pearce and J. Modrovsky. (Proceedings of the Society for Experimental Stress Analysis, 1945, vol. 3, No. 1, pp. 81–93). An experimental method of determining crankshaft main-bearing loads and stresses is described wherein the model is made of plastic to permit the use of smaller applied loads and simplified test equipment.

Stress Analysis of Shafting Exemplified by Saint-Venant's Torsion Problem. T. J. Higgins. (Proceedings of the Society for Experimental Stress Analysis, 1945, vol. 3, No. 1, pp. 94–101). A review is presented of the literature on procedures, curves, formulæ and test data for calculating the stress distribution and maximum stress in filleted, stepped, collared, grooved, slit, and notched shafting.

Dynamic Stress Analysis with Brittle Coatings. G. Ellis and F. B. Stern, jun. (Proceedings of the Society for Experimental Stress Analysis, 1945, vol. 3, No. 1, pp. 102–111). Examples are given of the use of brittle coatings for determining stresses under dynamic conditions. The examples include the stress on a shot-gun during firing and the analysis of the failure of aircraft landing gear.

The Structural Analysis and Significance of Rivet Shear Tests. G. E. Holback. (Proceedings of the Society for Experimental Stress Analysis, 1945, vol. 3, No. 1, pp. 131–154). A simple and effective method of analysing shear-test data for rivets is presented. The non-dimensional nature of this analysis also provides the basis for an analytical approach to the prediction of the structural characteristics of the rivet.

Mild Steel and its Properties, with Special Reference to Its Working and Age-Hardening. C. A. Edwards. (Institute of Vitreous Enamellers: Foundry Trade Journal, 1946, vol. 78, Jan. 24, pp. 83–84). The rôle which titanium plays in ordinary low-carbon steels is discussed. Titanium steel shows no yield point when strained, and does not display any tendency to strain-age-hardening.

X-Ray Stress Measurements at the Beginning of Flow in Carbon Steel. R. Glocker and H. Hasenmaier. (Zeitschrift des Vereines deutscher Ingenieure, 1940, vol. 84, Oct. 26, pp. 825–828). Measurements of the internal stresses in low-carbon unalloyed steels were made using cobalt and chromium radiation, which have different penetrations. It was found that flow began in a 0·01-mm. surface layer at a stress which was only 50–66% of the elastic limit; this applied both in tensile and torsional tests.

The Effect of Periods of Rest on the Time-Resistance and Fatigue Strength of Metallic Materials. F. Bollenrath and H. Cornelius. (Zeitschrift des Vereines deutscher Ingenieure, 1940, vol. 84, May 4, pp. 295–299). Tensile fatigue tests were carried out on specimens of a number of metals and alloys representing a wide variety of lattice structures and mechanical properties, and the effects of periods of rest on the ability of the material to resist a limited number of reversals at above the fatigue strength (*i.e.*, the time-resistance). The test data indicated that rest periods had no effect on the Wöhler curves.

The Effect of Overstress in Fatigue on the Endurance Life of Steel. J. B. Kommers. (American Society for Testing Materials, 1945, Preprint No. 23). The results of an investigation of the effects of overstress in fatigue tests are reported, and these indicate that, in general, when a high overstress has produced a certain percentage of damage to the endurance life, a subsequent lower overstress will show a greater percentage of damage. In the latter case the damage

may be four times greater at the final stress than at the initial stress. On the other hand, when a low overstress is followed by a higher one, the damage to the endurance life is less at the final stress than at the initial one. When the initial overstress is low and the number of cycles not too large, the effect of the initial stress is to increase the endurance life at the final stress. This increase may exceed 100%.

A Sulfur Print Method for the Study of Crack Growth in the Corrosion-Fatigue of Metals. R. C. Brumfield. (American Society for Testing Materials, 1945, Preprint No. 28). A sulphur-printing technique and its application to study corrosion-fatigue damage in specimens of a chromium-molybdenum steel are described.

Work Hardened Surfaces of Fatigue Specimens. F. C. Hull and H. R. Welton. (Metal Progress, 1945, vol. 48, Dec., pp. 1287–1289). A brief account is given of an investigation of the work-hardening effect produced by rough-machining and fine-machining in the preparation of fatigue-test specimens. Rough-machining hardens the material to a greater extent than fine cuts, and even fine-machining hardens steel to a depth of several thousandths of an inch.

X-Ray Diffraction Applied to Shot-Peened Surfaces. E. W. Milburn. (Metal Treatment, 1945, vol. 12, Winter Issue, pp. 259–260). It is well known that the creation of residual compressive stresses by shot-peening the surface of steel will greatly increase its resistance to fatigue. This treatment, however, produces a rough surface; the question therefore arises whether the rough surface can be removed and the high compressive stresses retained. An investigation of the changes in the compressive stress with increasing depth from the surface of a 4-in. shot-peened beam of chromium-molybdenum steel was carried out by the X-ray diffraction technique. The stresses introduced by the shot-peening treatment extended to approximately 0·009 in. A layer 0·005 in. thick could be removed from the surface without diminishing the effectiveness of the shot-peening by more than a few per cent.

A Dynamic Pull-Push Testing Machine for Determining Fatigue Strength and the Damping Capacity of Materials. M. Russenberger. (Schweizer Archiv, 1945, vol. 11, Feb., pp. 33–42). A detailed description is given of a high-frequency electro-magnetic fatigue-testing machine with which specimens can be loaded at up to 1000 kg. at between 50 and 200 reversals/sec. Fatigue-test data obtained with it are presented and discussed and the application of the machine to study damping capacity is described.

Damping Capacity. L. Rotherham. (Metal Treatment, 1945, vol. 12, Winter Issue, pp. 215–222, 232). The engineering and physical aspects of damping are considered and experimental methods for its determination are described. The effects of the carbon and chromium contents of steel as well as the influence of cold-work and the magnetic properties on damping are dealt with.

Microhardness Testing. E. O. Bernhardt. (Zeitschrift des Vereines deutscher Ingenieure, 1940, vol. 84, Sept. 28, pp. 733–736). The construction of the Zeiss microhardness testing instrument is described and its application to study the increase in hardness of cold-worked surfaces is discussed with examples which include an examination of the hardness of shot-blasted wire for valve springs and of rolled threads on chromium-vanadium steel bolts.

Hardness Testing. (Iron and Steel, 1946, vol. 19, Jan., p. 2). A new hydraulically operated semi-automatic machine for making Brinell hardness tests is described.

Testing Depth of Hardness. L. Sanderson. (Metal Treatment, 1945, vol. 12, Winter Issue, pp. 272–274). The use of hardenability in steel specifications is discussed and details are given of the A.S.T.M. standardized procedure for carrying out the Jominy end-quench test.

Remarks on Structural Hardening. A. Portevin. (Revue de Métallurgie, Mémoires, 1944, vol. 41, Feb., pp. 42–44). According to the author's definition the term structural hardening means the increase of Brinell hardness resulting from a modification of the micrographic structure only, *e.g.*, from the heat-treatment which produces troostite or sorbite. On the other hand, the martensitic hardening of steel, which causes a change in the nature of the constituents and in the crystalline network, the author classifies as physico-chemical hardening.

The Mechanism of Brittle Fracture. G. S. Smith. (Metallurgia, 1945, vol. 33, Dec., pp. 55–58). Evidence of the actual process of fracture of brittle materials is not easy to obtain, but recent study of the subject has introduced a new conception of fracture which assists the acceptance of a theory developed 25 years ago by A. A. Griffiths. Particular attention is directed to recent work the results of which appear to establish, with certain kinds of materials, the rôle of external and internal defects during fracture and the order of formation of the parts of the new surfaces.

Contribution to a Study of Brittleness. J. Pomey. (Revue de Métallurgie, Mémoires, 1944, vol. 41, Jan., pp. 17–25; Feb., pp. 49–59; Mar., pp. 83–94). The author reports on a comprehensive investigation of impact strength carried out in the Research Department at the Renault Works in France. Special attention is paid to the impact value in the transverse direction, and the relation between fatigue limit and hardness with reference to the tempering temperature is discussed. A comparison is made between "Uf" and Mesnager specimens for impact testing. The position of the notch, which may be perpendicular or parallel to the grain flow, was examined and the best results were obtained with test-pieces notched perpendicularly to the grain flow. In the last section of the article the author, having proved that the classic methods of impact testing are inadequate for the determination of brittleness, shows that a method can be evolved which, by changing the sharpness of the notch, gives, by extrapolation, the technical cohesive strength of the material.

A Case of Embrittlement of Steel. (Monthly Review of the American Electroplaters' Society, 1945, vol. 32, Aug., pp. 784–786, 845). A zinc-plated spring clip exhibited a stained fracture which was found to be partly intercrystalline in areas adjacent

to spot welds. This condition may be due to local hydrogen embrittlement during plating which in turn may be due to occlusion of hydrogen in microscopic intercrystalline cracks produced in or near the welds during welding. It is probable that clips with sound non-martensitic welds, which might be obtained by preheating prior to spot-welding, would withstand zinc plating without cracking.

Temper Brittleness. J. H. Holloman. (American Society for Metals, Oct., 1945, Preprint No. 11). Recent literature on temper-brittleness is critically reviewed. It appears that this phenomenon is caused by a precipitation from α-iron which occurs preferentially at the grain boundaries. The assumption that the precipitate is a phase consisting of iron and an element which supersaturates α-iron at low temperatures is consistent with the known facts. Above about 600° C. the solubility of the element in steels responsible for temper-brittleness is such that the embrittling precipitate redissolves. At temperatures just below the solubility limit the precipitation takes place very slowly, for the rates of both nucleation and growth are small.

The Magnetic Hardness Testing of High-Speed Steels. H. Springer. (Zeitschrift des Vereines deutscher Ingenieure, 1940, vol. 84, June 1, pp. 365–370). The relation between the magnetic permeability of steel and its hardness is discussed and an instrument is described with which the changes in permeability at each stage of heat-treatment can be followed. The application of this principle to the development of a heat-treatment for high-speed steel is considered.

The Effect of the Field Distribution on the Detectability of Flaws in the Magnetic-Powder Method of Testing. E. A. W. Müller. (Zeitschrift des Vereines deutscher Ingenieure, 1940, vol. 84, July 6, pp. 472–476). The magnetic-powder testing of crankshafts is discussed with special reference to the changes in technique when testing short and long shafts with marked variations in section between the wrist pins and the webs.

Crack Detection—Metrolux Fluorescent Equipment. (Iron and Steel, 1945, vol. 18, Dec., p. 634). The procedure for detecting cracks on a metal surface by impregnating the specimen with a fluorescent compound and then cleaning, drying, and inspecting it under ultra-violet light is described.

The Brittleness and Toughness of Metals at High Temperatures. W. Siegfried. (Schweizer Archiv, 1945, vol. 11, Jan., pp. 1–16; Feb., pp. 43–61). An earlier investigation in the laboratories of Gebrüder Sulzer led to the conclusion that the rapid decrease in the strength of notched specimens and the brittle intercrystalline fractures obtained in unnotched specimens after long periods under load are a result of the same internal phenomena. Two extensive series of creep tests are now described. Tin-cadmium alloys were used in the first series because they behave at room temperature in the same way that steel does at high temperature; cold-drawn as well as heat-treated specimens, notched and unnotched, were tested to examine the effect of the microstructure. In the second series, notched steel specimens were prepared with twelve different notch contours so as to study the effect of the notch angle and the radius at the bottom of the notch. The results proved that the embrittlement followed physical laws which embrace not only low-alloy steels at 500° C., but also the tin alloys. Additional tests at 650° C. on 30/15 and 12/15 austenitic chromium-nickel steels proved that the results with the softer materials were also applicable to austenitic steels.

A method of determining the behaviour of steels at high temperatures which does not involve creep tests lasting several thousand hours is described. Creep tests are made on unnotched specimens; the total elongation at fracture and the reduction in area are measured; these values are used to calculate the uniform elongation and the local elongation by Kuntze's formula. The necking elongation divided by the uniform elongation is thus a measure of the cohesion of the steel.

Structural Changes in Carbon and Molybdenum Steels during Prolonged Heating at 900° to 1100° F., as Affected by Deoxidation Practice. G. V. Smith, R. F. Miller, and C. O. Tarr. (American Society for Testing Materials, 1945, Preprint No. 19a). Annealed and normalized specimens of nine steels (three with carbon 0·1% and six with carbon 0·1–0·2% and molybdenum 0·5%), prepared with different deoxidation practices, were given hardness tests and their microstructures were examined after holding at 900°, 1000°, and 1100° F. for periods up to 5000 hr. The hardness of most of the carbon steels at first increased slightly with time at temperature and then decreased slowly; this behaviour appeared to be unaffected by the deoxidation practice used. The increase was greatest in the annealed samples held at 1000° F. The hardness of the annealed molybdenum steels followed the general pattern of the carbon steels, but the normalized specimens behaved in a manner characteristic of precipitation-hardening systems.

Wrought Heat Resisting Alloys for Gas Turbine Service. C. T. Evans, jun. (Metal Progress, 1945, vol. 48, Nov., pp. 1083–1095). The metallurgy involved in the development and selection of alloys for service at high temperatures, especially for gas turbines, is examined. If premature failure is to be avoided, numerous and complex factors must be taken into account. Short-time tensile, creep and fatigue test data, physical constants, and information on oxidation resistance on 15 of the older alloy steels are presented and discussed.

German Stainless Steels. A. L. Feild. (Iron Age, 1945, vol. 156, Dec. 20, pp. 60–67). Data on the properties, applications and methods of processing and heat-treating the various types of stainless and heat-resisting alloy steels which were commercially produced in Germany during the war, are presented. Scarcity of alloying agents such as molybdenum, nickel and niobium led to the development of low-alloy heat-resistant stainless steels or to the replacement of such elements with manganese, titanium and vanadium. Information on the properties of the steels is presented in seven comprehensive tables.

The Heat-Treatment of Low Alloy Wrought Steels. (Metallurgia, 1945, vol. 33, Dec., pp. 73–78). Particulars are given of the properties which can be

developed by applying suitable heat-treatments to several of the "En" low-alloy steels in the British Standards 970 and 971.

Nickel- and Molybdenum-Free Constructional Steels. H. Kiessler. (Zeitschrift des Vereines deutscher Ingenieure, 1940, vol. 84, June 8, pp. 385–392). The properties and heat-treatment of low-alloy chromium-manganese steels which have been developed in Germany are discussed.

Alloy Steel or Alloy-Treated Steel (?). H. T. Chandler. (Metal Progress, 1945, vol. 48, Nov., pp. 1104–1108). The author differentiates between steel containing alloying elements the purpose of which is to impart certain properties to the steel, and those treated by the addition of agents containing elements for controlling the deleterious effects of sulphur, phosphorus and nitrogen, as well as the grain size. He suggests that carbon steels and the standard alloy steels be specified by their chemical analysis, but that no effort be made to specify a chemical analysis for the residual amounts of addition agents in "alloy-treated" steels which is the term recommended for the second of the above classes of steel.

Wear Resistant Steel Castings for the Mining Industry. J. E. Norman. (Metallurgia, 1945, vol. 33, Dec., pp. 83–84). Most of the wear-resistant castings used by the mining industry are made from alloy steel, either of the austenitic Hadfield manganese type or of one of the lower alloy types in which the composition and heat-treatment are designed for the purpose. The low-alloy steels are favoured by the mining industry as they offer more advantages than austenitic manganese steels. Better machinability and wear resistance, high yield strengths, ease of production, desirable magnetic properties and low first cost are some of the advantages of the former. A brief summary is given of certain types of chromium-molybdenum low-alloy steels which have shown outstanding merit in the mining industry.

Fracture Testing of Alloy Steels for Aircraft Engine Forgings. R. D. Haworth, jun., and A. F. Christian. (American Society for Testing Materials, 1945, Preprint No. A4). Fractures of highly stressed aircraft engine parts have exhibited an unusual appearance characterized by large grains or facets. Photographs of fractures after various heat-treatments are shown and a complete set of fracture-test standards are presented. The operation of the test in production, and results obtained with it, are described.

A Critical Survey of Steel Specifications. R. A. Hoskins. (Australian Institute of Metals: Australasian Engineer, 1945, Nov. 7, pp. 79–85). Steel specifications in England, Australia, and the United States are reviewed. In England the efforts to correct the over-diversification apparent in the pre-war years have been reasonably successful. The British Standard 970-En Series is the most outstanding set which has been evolved, and it is hoped that the ranges of analyses and mechanical properties employed therein will form the basis of most of the post-war general engineering, automotive and aircraft specifications, both in Great Britain and Australia.

METALLOGRAPHY AND CONSTITUTION

(Continued from pp. 31 A–32 A)

Etching for the Microscope. Part I. Iron and Steel. C. A. E. Wilkins. (Metal Treatment, 1945, vol. 12, Winter Issue, pp. 233–241). The purposes of etching and the methods employed are dealt with and the etching of cast iron is then discussed, numerous etching reagents being recommended. A table is included giving heat-tints on grey cast iron at various temperatures. The etching of stainless and high-speed types of steel is also considered.

Continuous X-Ray Inspection. D. Goodman. (Canadian Metals and Metallurgical Industries, 1945, vol. 8, Nov., pp. 32–35, 52). A description is given of the system of continuous X-ray inspection which was installed at one of the largest munition plants in the United States for examining large bombs and shells. A 2000-kV. X-ray unit is employed. The portion of the X-ray beam which is reflected from the anode of the tube is used for the radiography of shells which are carried round the unit on a continuous ring conveyor. The screening and safety methods employed are also described.

X-Ray Diffraction in Inorganic Chemistry, Metallurgy and Mineralogy. H. Lipson. (Nature, 1946, vol. 157, Feb. 2, pp. 124–126). This review of the applications of X-ray diffraction is based on papers presented by A. F. Wells, W. H. Taylor, and the author at a meeting held recently at the Royal Institution. The fundamental importance of X-ray diffraction lies in the insight it gives into atomic arrangements. Work on nickel-aluminium and copper-aluminium alloys is referred to. Many interesting types of diffraction effects have been observed in the study of silicates and these throw light on the mechanism of isomorphous displacement.

Accurate Interpretation of Radiographs. H. R. Clauser. (Engineering Materials and Processing Methods, 1945, vol. 22, Nov., pp. 1418–1422). Definitions are given of a number of terms used in the interpretation of radiographs and the conditions necessary for viewing radiographs are described.

Estimation of Spatial Grain Size. W. A. Johnson. (Metal Progress, 1946, vol. 49, Jan., pp. 87–92). Quantitative relationships may exist between the grain size and properties of a metal or alloy, but their determination is contingent on having more precise means of evaluating grain size than those now available. In this paper details are given of a method of determining the distribution of "spatial" grain sizes from the relative areas of each size of the grains shown in a micrograph. The method is based on the results of statistical observations of structure by E. Scheil and A. Lange-Weise (*see* Journ. I. and S.I., 1937, No. II., p. 247 A).

Effect of Cooling Transformation upon Subsequent Isothermal Reactions. C. A. Liedholm and W. C. Coons. (Metal Progress, 1946, vol. 49, Jan., pp. 104–

107). The importance of paying adequate attention to the differences between the time-temperature cycle of a part to be heat-treated and the time-temperature cycles whereon the S-curve for the particular steel is based is stressed, and two examples are cited in which the structures obtained were not those predicted from the S-curves.

CORROSION OF IRON AND STEEL

(Continued from p. 33 A)

The Corrosion of Iron and Steel. J. C. Hudson. (Journal of Scientific Instruments, 1945, vol. 22, Dec., pp. 231–235). A broad outline of the work and activities of the Corrosion Committee (a Joint Committee of The Iron and Steel Institute and The British Iron and Steel Research Association) is presented.

Recent Russian Work on Corrosion. (Conference on Corrosion, Moscow, 1943: Chemical Age, 1946, vol. 54, Jan. 5, pp. 5–8). A condensed version is given of a paper by T. A. Adjemyau on the corrosion resistance of different materials employed in the construction of plant for Russian chemical industries. It deals with the production of halogen salts such as chlorides, sulphur compounds, fluorine compounds, halogen compounds of the iodo-bromine type, and general research on materials liable to corrode.

A Theory of the Mechanism of Rusting of Low Alloy Steels in the Atmosphere. H. R. Copson. (American Society for Testing Materials, 1945, Preprint No. 25). Exposure tests were started in 1941 on low-alloy steels in industrial and marine atmospheres. Analyses of samples of rust, weather data, and losses in weight are considered. It is postulated that the rate of corrosion depends on the quality and quantity of the water reaching the surface. Relatively insoluble corrosion products decrease the amount of soluble constituents in the water and thereby decrease the corrosion. Relatively insoluble corrosion products do not wash away, so that the porosity of the rust coating and the quantity of water reaching the steel are decreased. In industrial atmospheres, copper and nickel in the steel render sulphate corrosion products more insoluble by forming complex basic sulphates. On mild steel, sulphates in the rust are relatively soluble and promote corrosion, but are washed away by rain. On alloy steels the sulphates are less soluble so that corrosion is slower, but less sulphate is washed away and more accumulates in the rust. The percentage of sulphates in the rust increases as the loss in weight decreases. It has been tacitly assumed that, in a given atmosphere, each test specimen of steel is exposed to the same environment; actually, owing to the influence of corrosion products, each specimen is exposed to a separate environment.

Inhibition of the Corrosion of Metals in Contact with Water and/or Steam. W. Murray. (Association of British Chemical Manufacturers: Steam Engineer, 1946, vol. 15, Jan., pp. 117–118). Recommendations on methods of reducing the corrosion of metals by water and steam are made. Keeping up the pH value of the water and adding tannin is advocated for the prevention of "graphitic wastage" in cast-iron economizers.

Controlling Factors in Atmospheric and Immersed Corrosion. W. H. J. Vernon. (Journal of Scientific Instruments, 1945, vol. 22, Dec., pp. 226–230). Factors are discussed which, although apparently subsidiary, are responsible for controlling the rate of corrosive attack under a given set of conditions. The hydrogen-evolution and the oxygen-absorption types of immersed corrosion are dealt with. In the former type it is rare to have an obstructive film at the anode; most frequently the obstruction occurs at the cathode and is associated with the phenomenon of hydrogen overpotential. In the latter type there are two well-known controlling factors, namely, an obstructive film at the anode, and the rate of supply of oxygen to the cathode. In atmospheric corrosion the frequently encountered controlling factor, far from being the rate of oxygen supply, is the rate of supply of water. In the case of iron and steel the controlling factor at high relative humidities is provided entirely by the state of purity of the atmosphere. The growth of air-formed oxide films and the significance of rectilinear, parabolic, logarithmic, and asymptotic oxidation-time curves are considered.

Electrochemical Measurements for Corrosion Studies. P. T. Gilbert. (Journal of Scientific Instruments, 1945, vol. 22, Dec., pp. 235–237). A detailed description is given of an apparatus which was set up to study the behaviour of pairs of coupled metals in tap water to establish the relationships between them as they corroded with different concentrations of dissolved oxygen and carbon dioxide in the water. The potentials and corrosion currents from four couples of corroding metals were simultaneously and continuously recorded.

The Corrosive Action of Benzole Absorption Oils. (Coke and Smokeless Fuel Age, 1946, vol. 8, Jan., pp. 17–18). Two reports of independent research work on the corrosive action of benzole absorption-oils have recently been published, one by O. B. Wilson, and the other by C. M. Cawley and H. E. Newall (*see* Journ. I. and S.I., 1945, No. II., p. 69 A and 1946, No. I., p. 33 A). The conclusions reached are compared and discussed in the present paper.

Intercrystalline Cracking. C. D. Weir. (Mechanical Engineering, 1945, vol. 67, Dec., pp. 834–835). The effect of the silica/sodium-hydroxide ratio in the feed water on the susceptibility of boiler steel to cracking is treated statistically and diagrams showing the boiler conditions (*i.e.*, pressure, sodium-hydroxide concentration, and the above ratio), in relation to the cracking of boiler plates are presented. It is concluded that this ratio does not influence the frequency with which intercrystalline cracking occurs.

The Behaviour of Zinc-Iron Couples in Carbonate Soil. J. H. Gilbert and G. Corfield. (Corrosion, 1945,

vol. 1, Dec., pp. 187–191). The behaviour of zinc in contact with steel in soils, important from the standpoint of the cathodic protection of pipe lines, is described. Each couple consists of an iron ring connected to one or more zinc cylinders, and the entire surfaces of the iron rings were in contact with a "high-carbonate" soil near Los Angeles for 546 days. The variations in current, the electrode potentials, and the loss in weight of the metals were determined.

Marine Corrosion Testing Station at Kure Beach, North Carolina. (Corrosion, 1945, vol. 1, Dec., pp. 178–186). The sea water corrosion-testing station at Kure Beach is described, with numerous illustrations (*see* Journ. I. and S.I., 1945, No. II., p. 150 A).

Recommendations on Methods of Protection against Corrosion for Light Gauge Steel and Wrought Iron Used in Permanent Building Construction. (British Standards Institution, 1945, P.D. 420). This pamphlet is not a specification, but is to be regarded as a reasoned statement of recommended procedure for the protection of light gauge wrought iron or steel sections or sheets as used in building construction, more particularly for dwelling houses.

BOOK NOTICES

(Continued from p. 35 A)

Barr, W., and A. J. K. Honeyman. "*Steel and its Practical Applications.*" Second Edition. 8vo, pp. xii + 156. Illustrated. London and Glasgow, 1945 : Blackie and Son, Ltd. (Price 8*s*. 6*d*.)

Since the first edition of this book, considerable changes and advances have been made in ferrous metallurgy. The war has been responsible especially for a changed outlook regarding alloy steels, hardenability, weldability and creep. This second edition, which contains brief accounts of these modern trends, should be welcomed by engineers. The chapters dealing with carbon and alloy steels have been brought up-to-date by the inclusion of details of the new "En" steels. It has been necessary to enlarge the chapter on heat-treatment to include reference to isothermal-transformation (or S) curves, and the Jominy test for hardenability.

New chapters have been added dealing with the factors influencing the creep strength of steel and metallurgical aspects of gas-cutting and welding high-tensile steels. The illustrations are of good quality, but it would facilitate reading if the position of the plates was near the text.

E. C. Rollason.

Rolfe, R. T. "*A Dictionary of Metallography.*" 8vo, pp. viii + 243. London, 1945 : Chapman & Hall, Ltd. (Price 15*s*.)

The evolution of any branch of physical science inevitably calls into existence a specialized terminology, in which familar words may have circumscribed meanings, and new words may have been coined to describe new facts and phenomena. Metallography had a flying start as regards nomenclature, for almost the first terms used in the infancy of the science were the personal inventions of the pioneer metallographists, giving us the now familiar names for the microscopic constituents of steel. Metallography now is, as the author of this dictionary points out in his foreword, a division of metallurgical science difficult to define, as it undoubtedly reaches out and touches the fringes of many other sciences, so that the necessary vocabulary includes many terms in general scientific use, and thus an exhaustive dictionary of the subject would be indeed a formidable work. The author makes no claim to exhaustiveness in this sense, and having resigned himself to certain deliberate omissions, has covered the remaining field in a thorough manner. It may at once be said that no serious omission of any metallurgical term was noted, and the fairly generous treatment given to the vocabulary of most of the ancillary sciences should satisfy the great majority of enquirers.

Indeed, so wide is the net cast by the compiler that the reviewer seriously questions the accuracy of his title, notwithstanding the plea advanced in the foreword for a generous interpretation of the term "metallography." Premeditated omissions can readily be accepted if the very best use is made of the available space, but it is debatable whether the author is justified in allowing some descriptions of manufacturing processes and data on the properties, occurrence, and extraction of the metallic elements to displace all reference to, for example, the magnetic properties of metals or microscope optics.

Every lexicographer, from Dr. Johnson onwards, has had to face the heavy task of maintaining unrelenting accuracy. A dictionary is nothing if not reliable, and Mr. Rolfe comes very well out of the most exacting factual enquiry that the reviewer could apply. It is therefore with due deference to the predominating success achieved by the author that some lapses are mentioned. Thus, the well-known S.80 composition of stainless steel is included under the term "Stainless Iron," a classification that is at variance with its properties and with the general position accorded to this alloy in specifications and normal engineering parlance. Again, the statement "In their shorter reaches, ultrasonic waves merge with radio and finally with light waves" is made under "ultrasonics." Neither sonic nor ultrasonic waves have any place in the electromagnetic wave spectrum. Lastly, the author, under "Charpy Impact Test" rather inexplicably cites the Addendum of March 1942 to British Standard 131–1933 as referring to Charpy test-pieces with the Charpy keyhole notch, whereas the publication mentioned specifies the Mesnager type notch and the two are not interchangeable.

The book is well bound and clearly printed, the item headings standing out well on each page. The alphabetical arrangement naturally provides its own index, and cross indexing is freely provided when synonymous terms are defined. The author makes use of standard definitions where possible, mainly from American sources, many of these relating to the growing technology of powder metallurgy. The reviewer found rather distracting the practice of using only the initial letters of the item headings, when the same words recur in the text, although this is common in ordinary dictionaries, but surely such compression is carried too far, when nickel is rendered as "n" in place of the universally acceptable "Ni."

S. L. Roberton.

REFRACTORY MATERIALS

Steel Plant Refractories. J. H. Chesters. (British Engineering Export Journal, 1946, vol. 28, Jan., pp. 428–433). Recent improvements in the manufacture of steel-plant refractories, including the control of quality by statistical methods, are pointed out. Methods of testing bricks and the properties of magnesite and carbon refractories are discussed.

Potmaking. (British Steelmaker, 1946, vol. 12, Jan., pp. 24–25). A detailed description is given of the production of crucibles for steelmaking.

Recent Progress in the Manufacture of Refractories for Metallurgy. Y. Lefort. (Revue de Métallurgie, Mémoires, 1942, vol. 39, May, pp. 141–151; June, pp. 172–180; July, pp. 201–210). Three main groups of refractories, i.e. the alumina, silica and magnesite types, are discussed in detail. Their nature, structure and behaviour at high temperatures are examined, and the progress in their manufacture reviewed. In conclusion the importance is stressed of scientific investigations, such as thermal analysis, microscopical examination and X-ray testing, for the development and improvement of refractories.

Carbon Lining for Blast Furnaces. F. G. Vosburgh. (Steel, 1945, vol. 117, Dec. 24, pp. 86–90; Dec. 31, pp. 62–63, 78–80). The history of the use of carbon linings for blast-furnace hearths in the United States is outlined, and descriptions are given of the blocks used, the positions of the joints, and the carbon ramming mix.

Statistical Treatment of Laboratory Test Data on Refractories. J. H. Chesters and I. M. D. Halliday. (Transactions of the British Ceramic Society, 1945, vol. 44, Sept., pp. 135–166). Research on refractories is passing from a qualitative to a quantitative stage. Variability, both in the product and in operating conditions must be measured and allowed for. This requires the application of statistics. The use of histograms, in which the frequency with which particular values of a property occur is indicated by vertical strips, often gives a qualitative answer, but the calculation of the arithmetic mean, the standard deviation and the range are often used in support. Quality control charts are shown to provide a rapid method of deciding whether the product under test differs significantly in properties from that received previously. It is also shown that arithmetic probability paper affords a ready means of comparing data of the normal distribution type, particularly as it enables quick estimates to be made of the rejections that would occur at various levels of control. It is shown that apparent differences between the quality of dolomite received during two periods may be due to inadequate sampling. The use of correlation coefficient is illustrated with reference to the close relationship between the bulk density and thermal conductivity of diatomite bricks.

Statistical Data Relative to the Firing Expansion, Specific Gravity and After-Expansion of Silica Bricks. T. R. Lynam and I. M. D. Halliday. (Transactions of the British Ceramic Society, 1945, vol. 44, Oct., pp. 167–202). It is regarded as unsatisfactory that the quality of a wagon-load of silica bricks for the gas industry is judged by destructive tests on two bricks selected at random. If a definite relationship could be proved to exist between the firing expansion (linear) which occurs in the kiln and the specific gravity of the fired product, the simple expedient of measuring a brick should be an efficient test of the heat-treatment it has received. It would then be possible to apply this rapid test to a much larger number of samples. An account is given of a statistical investigation of test data on 200 random samples from different known positions in various kilns. The tests included kiln expansion (linear), specific gravity, and after-expansion. It was found that a significant relationship exists between the kiln-firing expansions and the specific gravities of silica products, and that the non-destructive measuring test can be applied to ascertain the heat-treatment.

Testing of Chrome-Magnesite Brick for Resistance to Iron Oxide Bursting. S. Zerfoss and H. M. Davis. (Journal of the American Ceramic Society, 1946, vol. 29, Jan., pp. 15–20). The probable mechanism of the iron-oxide bursting of chromium-magnesite brick is discussed. An attempt was made to duplicate this in the laboratory. The results indicated that the bursting can be simulated in a laboratory experiment, providing the atmosphere of the furnace is such that the penetrating iron oxide liquid is rich in magnetite. A test is proposed for characterizing the bursting resistance of various bricks.

X-Ray Diffraction Data for Compounds in the System CaO–MgO–SiO_2. C. B. Clark. (Journal of the American Ceramic Society, 1946, vol. 29, Jan., pp. 25–30). X-ray diffraction data for compounds in the system CaO–MgO–SiO_2 obtained by the powder method are widely scattered in the literature. In certain instances there is need of revision because of improvement in equipment and technique. X-ray powder photographs have therefore been made, and data are presented in this paper on nineteen compounds in this system. These represent all the known compounds which are stable, and several which are metastable, at room temperature.

FUEL

(Continued from pp. 37 A–38 A)

Problems in Fuel Efficiency. C. Hulse and R. J. Sarjant. (Iron and Steel Institute, 1946, this Journal, Section I.). Problems in fuel efficiency relating to works where processes may be specialized are discussed in relation to the bearing of fuel selection on efficiency, developments in furnace design and

construction, methods of fuel saving in individual works, education, and research. The present position is reviewed and lines of future development are suggested.

Heat Transfer. G. T. Skaperdas. (Industrial and Engineering Chemistry, Industrial Edition, 1946, vol. 38, Jan., pp. 10–11, 32, 33). Progress made during the last two years in the theory and practice of heat transmission are reviewed. There are 75 references to the literature.

The Influence of Tube Shape on Heat-Transfer Coefficients in Air to Air Heat Exchangers. F. H. Green and L. S. King. (Transactions of the A.S.M.E., 1946, vol. 68, Feb., pp. 115–122). Heat-transfer coefficients are reported for air passing through round tubes, through partially flattened tubes, and through partially flattened tubes which have been dimpled. It was found that flattened tubes maintained fully turbulent flow, and that they therefore had a higher heat-transfer coefficient at lower Reynolds numbers than round tubes. The addition of dimples to the flattened tubes maintained fully turbulent flow from the transition point and increased the heat-transfer coefficient substantially. The addition of the dimples also improved the relation between the heat transfer and the pressure drop in the flattened tubes.

Problem of Flame Radiation, with Particular Reference to Melting Furnaces. T. F. Pearson. (Iron and Coal Trades Review, 1946, vol. 152, Mar. 1, pp. 381–385). To take the ratio of useful heat output to the total heat input as the measure of the efficiency of a gas-fired furnace is not altogether adequate, since the degree of heat transfer from the flame and walls tends to be overlooked. This detail of the simplified conception of furnace efficiency is of greater importance in high-temperature melting furnaces than in low-temperature heat-treatment furnaces. Reasons for this are given in the present paper and the possibilities of increasing the thermal efficiency by modifying the flame are discussed.

Combustion Control. (Steel, 1945, vol. 117, Dec. 10, pp. 134–139). Three methods are described which are used for combustion analysis in open-hearth furnaces, soaking pits, treating furnaces, steam power plants, and internal combustion engines. In particular, an instrument is described which has two dials; one indicating the percentage of unused combustible gases and the other the percentage of excess oxygen which may be present in the spent gases. These direct readings can be made at any instant from samples taken from any part of the furnace, flue or exhaust.

Conservation of Coal. A. C. Pasini. (Iron and Steel Engineer, 1946, vol. 23, Jan., pp. 112–114). Recommendations are made for obtaining the most efficient combustion of coal and for maintaining boilers in proper working condition.

Tubular Metallic Recuperators. G. N. Critchley. (Institute of Fuel Wartime Bulletin, 1946, Feb., pp. 100–119). A comprehensive discussion of the factors influencing the design and use of metallic recuperators is presented in four parts. The first three parts are of a mathematical nature and give methods of answering the following questions: (1) How much heat does the waste gas contain? (2) How much heat could be returned to the furnace by (*a*) the combustion air, and for (*b*) the fuel? (3) What, in given circumstances, is the most suitable design of recuperator? In the fourth part the economic aspects of recuperation are discussed.

An Experimental Determination of the Factors Governing the Design of Regenerators with Special Reference to Coke Ovens. T. C. Finlayson and A. Taylor. (Journal of the Institute of Fuel, 1946, vol. 19, Feb., pp. 82–98). After outlining the general principles of a regenerator, defining regenerator efficiency and briefly reviewing the literature, a report is presented on an investigation at a specially built test plant. The main object was to find the effect and quantitative value as regards heat transfer and pressure loss of the different factors in the design of both double-staggered checkers and straight-through or any other promising types of fillings, so that it would be possible to calculate the effect of any variations in design, and to indicate the most profitable lines for the development of coke-oven regenerators.

The Economic Limits of Separation of Middlings in Dense Medium Washers. K. F. Tromp. (Journal of the Institute of Fuel, 1946, vol. 19, Feb., pp. 112–115). When the middlings are used as a boiler fuel the separation between the middlings and the shale should be chosen at a density where the middlings have such a high ash content that the cost of industrial firing just equals the amount of its heat contribution. This ultimate allowable ash content, called the "economic firing limit" was originally assessed by Haarmann at 65% when the middlings are fired at the colliery. The author has reinvestigated the various factors involved, and arrives at the conclusion that normally the density cut will be much lower (at about 56% of ash), but that under certain conditions higher ash contents (up to 70%) can still advantageously be fired. Due to the imperfection of coal-washing systems, the actual cut has normally to be located at a density other than that of the economic firing limit, in order to be certain that the economic loss due to migrated material is at a minimum.

The Newcastle Steel Works Cleans Coal. W. H. Wainwright and J. S. Ratcliffe. (B.H.P. Review, 1945, vol. 23, Dec., pp. 6–8). A description is given of the Barvoys coal-cleaning plant at the coke-ovens of the Broken Hill Proprietary Co., Ltd., Newcastle, New South Wales.

Pulverised Coal and the Modern Drop Forge. J. M. Austin. (Institute of Fuel Wartime Bulletin, 1946, Feb., pp. 122–130, 134). A detailed description is given of an installation of fifty furnaces fired by pulverized coal for heating forgings. They include both batch and continuous furnaces. Full details are given of the refractories and insulation used and of the measures taken to reduce slagging and the maintenance costs associated with it. The properties and preparation of the fuel and plant operation and performance are also dealt with.

The Agglutination and Swelling of Coking Coal. H. E. Blayden, H. L. Riley, and F. Shaw. (Fuel in Science and Practice, 1946, vol. 25, Jan.-Feb., pp. 13–24). The literature on agglutinating tests for coal is reviewed and some limitations of the British

Standard Method for determining the agglutinating value are pointed out. Experiments are described in which coke buttons were prepared from coal mixed with colloidal magnesium trisilicate, and crystalline and amorphous varieties of silica and alumina. The factors inherent in the coal itself which affect the strength of the coke button are: (*a*) The proportion and character of the agglutinating constituents, *i.e.*, the coking-coal bitumens; (*b*) an inherent strength factor possibly determined by the pressure on the coal during formation; and (*c*) the extent of the swelling during carbonization. Laboratory tests can provide a valuable guide to the correct choice of carbonizing conditions and proper blending to obtain a coke with optimum properties.

Coke Oven and B. F. Practice. J. H. Patchett. (Cleveland Institution of Engineers: Iron and Steel, 1946, vol. 19, Feb., pp. 63–68). A general survey of the progress in coke-oven and blast-furnace practice in Great Britain in recent years, with indications of the direction which future developments are likely to take, is presented.

Method for Obtaining Ammonium Chloride from Gas-Liquor. C. H. Bone. (Blast Furnace and Steel Plant, 1945, vol. 33, Dec., pp. 1507–1510). A method of recovering ammonium chloride, which is satisfactory for use in galvanizing flux, from the gas-liquor produced during the carbonization of coal is described. The process has been worked successfully on a pilot-plant scale.

PRODUCTION OF IRON

(Continued from p. 38 A)

The Profile of Blast Furnaces. V. Rémond. (Revue de Métallurgie, Mémoires, 1945, vol. 42, Feb., pp. 29–64). A report is presented on a comprehensive study of blast-furnaces. It contains: (1) A table of profiles of 56 French blast-furnaces; (2) a comparison of the dimensions of these blast-furnaces and of data on their operation; (3) data relating to the production and efficiency in various blast-furnace plants, and (4) the author's conclusions presented in the form of a study of blast-furnace parameters. Finally, the evolution of the blast-furnace profiles in France from 1920 to 1940 is described, and data relating to blast pressure are given.

Three Blast-Furnace Questions. O. R. Rice. (Blast Furnace and Coke Oven Association of the Chicago District and Eastern States Blast Furnace and Coke Oven Association: Blast Furnace and Steel Plant, 1946, vol. 33, Dec., pp. 1523–1529). The following three questions relating to blast-furnace operation are discussed: (1) Does easier driving reduce the coke rate per ton of pig-iron? (2) Do little furnaces have lower coke rates than big ones? (3) Does a relatively large working volume conduce to a lower coke rate? Data on these questions are presented and considered, and the following conclusions are reached: (1) Easier driving does seem to reduce the coke rate, but not to a practical or economic degree; (2) small furnaces seem to have a lower coke rate than large ones; and (3) relatively large working volumes appear to result in a lower coke rate.

Blowing Out of Blast-Furnaces. O. Becker. (Blast Furnace and Coke Oven Association of the Chicago District and Eastern States Blast Furnace and Coke Oven Association: Blast Furnace and Steel Plant, 1945, vol. 33, Dec., pp. 1530–1531). **Full Furnace Blowdown Method.** O. Becker. (Steel, 1946, vol. 118, Jan. 14, pp. 112–115). A method of blowing out a blast-furnace is described. The stack is kept full of nut coke which is wetted profusely in the skip. The blast is gradually reduced as the pressure drops, and after the last cast is made, the gas is drafted back, blowpipes are removed and the tuyeres are plugged. The coke may be quenched with water from above or below, but preferably, and with greater safety, steam can be used.

Use of Domestic Coke in Blowing a Blast Furnace. W. H. Burnett. (Blast Furnace and Coke Oven Association of the Chicago District and Eastern States Blast Furnace and Coke Oven Association: Blast Furnace and Steel Plant, 1945, vol. 33, Dec., pp. 1533). **Domestic Coke Blowout Method.** W. H. Burnett. (Steel, 1946, vol. 118, Jan. 14, pp. 109–110). A procedure for blowing out a blast-furnace using domestic coke is described. Clean-out blanks (coke without ore) are charged daily for several days before blowing out, and the limestone in the burden is reduced. When ready, domestic coke only is charged with sufficient water in the skip to keep the top temperature below 600° F. Blast is taken off after the last cast is finished, the top is opened and full steam is turned into the dust catcher. Water may be introduced through the top to cool the stack, in which case it is sufficiently cooled in about 18 hr. Two coolers are removed and a chute is put in position to discharge the water and nut coke into trucks.

Blowing Out a Blast Furnace Utilizing the Nut Coke-Hydraulic Wash-Out Method. J. R. Barnes. (Blast Furnace and Coke Oven Association of the Chicago District and Eastern States Blast Furnace and Coke Oven Association: Blast Furnace and Steel Plant, 1945, vol. 33, Dec., pp. 1535–1536). **Nut Coke Hydraulic Washout Method.** J. R. Barnes. (Steel, 1946, vol. 118, Jan. 14, pp. 110–112). The practice employed by the Republic Steel Corporation for blowing out blast-furnaces is described in detail. After the last cast the furnace is filled with nut coke, and cooling water and steam are injected, the procedure being similar to that described by W. H. Burnett (*see* preceding abstract).

The Krupp-Renn Process. (Iron and Coal Trades Review, 1946, vol. 152, Mar. 15, pp. 485–491). *See* p. 38 A.

Hot-Pressing of Iron Powders. O. H. Henry and J. J. Cordiano. (American Institute of Mining and Metallurgical Engineers, Technical Publication No. 1919: Metals Technology, 1945, vol. 12, Oct.). An

investigation is reported the purpose of which was to determine the properties of hot-pressed specimens of electrolytic iron powder. Three methods of supplying heat to the specimens during the pressing operation were employed, viz., induction, passing a current through the highly resistant mass of powder, and enclosing the entire die assembly in a furnace. Tensile, density, and hardness tests were conducted on the specimens. There was a decided increase in density with increasing temperature. The curves for tensile strength and elongation clearly show the advantages that may be gained from hot-pressing. The increase in the surfaces of the particles coming into contact and the increase in the diffusion rates with rising temperature under sustained pressure are mainly responsible for the intraparticle bonding.

Pressing Complicated Shapes from Iron Powders. C. G. Goetzel. (American Institute of Mining and Metallurgical Engineers, Technical Publication No. 1920 : Metals Technology, 1945, vol. 12, Oct.). Two processes for moulding complicated parts of uniform density from powdered metals are described in detail. The first refers to curved parts, and the second is especially adapted to parts having one or more recesses or steps.

FOUNDRY PRACTICE

(Continued from p. 39 A)

Gray Iron Acceptance Broadens. T. Barlow. (Foundry, 1946, vol. 74, Jan., pp. 70–75, 162). Developments in processes and equipment at American grey iron foundries during the war are reviewed.

What Type Charger and Charging Bucket. A. W. Gregg. (Foundry, 1945, vol. 73, Dec., pp. 84–87, 228–232). Factors affecting the selection of mechanical equipment for charging cupolas are discussed and a number of charging-bucket designs are critically reviewed.

Foundries of the Future. J. B. Lamenzo. (Foundry, 1945, vol. 73, Nov., pp. 84–87, 238–246 ; Dec., pp. 88–93, 258–262). Factors to consider in the installation of conveyor systems and other labour-saving equipment in the foundry are discussed.

Foundry Practice at Consolidated. T. R. Stanley. (Canadian Metals and Metallurgical Industries, 1945, vol. 8, Dec., pp. 24–26). A description is given of the foundry practice at the works of the Consolidated Mining and Smelting Company of Canada, Ltd., British Columbia, where a wide variety of iron, steel, and non-ferrous metal castings are made.

Wartime Foundries of China. E. K. Smith. (Foundry, 1945, vol. 73, Dec., pp. 83, 210–218). Some of the difficulties encountered and overcome during the war by foundries in China are described.

The Manufacture and Properties of Modern High-Strength Castings. Part I. Steel Castings. C. H. Kain. (Manchester Association of Engineers, Feb., 1946, Advance Copy). A general account of the production of medium and light steel castings is given. The properties and methods of testing are discussed, with special reference to the casting of test bars.

The Manufacture and Properties of Modern High-Strength Castings. Part 2. High Duty Cast Irons. J. J. Sheehan. (Manchester Association of Engineers, Feb., 1946, Advance Copy). Progress in the production of high-duty cast irons is reviewed, with notes on the properties of cast-iron valve-tappets, low-chromium irons for wear-resistance and high-silicon irons for heat-resistance. A syphon pouring arrangement for the cupola spout which separates the slag from the metal and creates a substantial head of incandescent slag in the cupola is described.

Some Notes on High-Duty Cast Irons. A. H. Horton. (Institute of British Foundrymen : Foundry Trade Journal, 1946, vol. 78, Feb. 14, pp. 169–171). Methods of making high-duty cast iron in the cupola with subsequent additions of inoculants are described, and the properties of the iron are discussed.

Malleable Industry Improves Plant Facilities. C. H. Lorig. (Foundry, 1946, vol. 74, Jan., pp. 92–96, 214–218). Some of the very modern equipment installed at American malleable iron foundries during the war is described and illustrated.

West Coast Steel Foundry Uses Large Furnaces. R. L. Collier. (Foundry, 1945, vol. 83, Dec., pp. 99–100). A brief description is given of the electric furnaces and equipment which were installed for a new steel foundry at Portland, Oregon, for casting stern frames and other heavy castings for the shipyards.

The Manufacture of Some Thin-Walled Steel Castings, with Notes on the Influence of Pouring Speed. The Foundry Practice Sub-Committee. (Journal of the Iron and Steel Institute, 1945, No. II., pp. 519 P–534 P). This paper is presented by the Foundry Practice Sub-Committee of the Steel Castings Research Committee. Short accounts are given of the moulding and founding procedures used at seven foundries in the production of thin-walled steel castings, and of the influence of the rate of pouring on the quality of the castings produced. With bomb castings, least difficulty was met with when the moulds were filled quickly, and also less trouble was encountered with hot steel. There was considerable scabbing with very slow casting or with very cool steel. High rates of pouring also reduced the number of rejections due to hot tears, pulls, and other defects, such as sand inclusions. Casting temperatures above 1580° C. gave better results than temperatures below, say, 1550° C. With axle cases, satisfactory castings were made over a wide range of pouring speeds, but it should be noted that the casting temperatures are available for only one foundry.

Steel Castings Find New Applications. C. E. Sims. (Foundry, 1946, vol. 74, Jan., pp. 76–81, 220–225). Wartime developments in the manufacture of steel castings in the United States are reviewed.

Brockhouse—Growth of a Great Polygon Industry. (British Steelmaker, 1946, vol. 12, Jan., pp. 10–16). A brief account (based on Compton Mackenzie's book " Brockhouse ") is given of the life and work of John

Brockhouse of West Bromwich, founder of the Company bearing his name. John Brockhouse became the central figure in a great industrial combination embracing twenty-five individual companies making iron and steel castings, heavy chain, and machinery of all kinds.

1944–45 Sintering Test. (American Foundryman, 1945, vol. 8, Dec., pp. 38–39). This paper is a short report by the Committee on Sintering Test of the American Foundrymen's Association; in it the causes of the "spotty burning on" of sand on a steel casting are examined. This defect is attributed to insufficient ramming.

Effective Use of Cereal Core Binders. A. E. De Clercq and T. Barlow. (Foundry, 1945, vol. 73, Dec., pp. 109, 192–210). The effect of corn-flour on the green strength, dry strength, permeability, baking time and surface hardness of core-sand mixtures is discussed and recommendations on the use of corn-flour as a binder are made.

Dust Removal at Belt Transfer Points. C. C. Hermann. (Foundry, 1945, vol. 73, Dec., pp. 107, 226–228). In mechanized foundries where the sand is conveyed on belts there is always dust at the end of the belt where the sand is tipped off on to another belt. Details are given of the design of hoods to place over the conveyors at these points.

High-Pressure Feeding of Static Molds. S. T. Jazwinski and S. L. Finch. (Iron Age, 1946, vol. 157, Jan. 10, pp. 59–63; Jan. 17, pp. 54–63). *See* p. 20 A.

The Feeding of Castings. R. W. Ruddle. (Institute of Australian Foundrymen: Foundry Trade Journal, 1946, vol. 78, Mar. 7, pp. 253–256). The mechanism of the solidification of metals in moulds is explained and the essential requirements for good feeding practice are pointed out, with notes on the dimensions and position of risers. Finally, the method of applying atmospheric pressure to blind risers by inserting a core of permeable material in the riser cover is described.

Some New Foundry Plant. (Engineer, 1946, vol. 181, Feb. 15, pp. 151–152). Illustrated descriptions are given of new core-blowing, core-making and shot-blasting machines which have been developed by a Birmingham company.

The Formation of Banded Structures in Horizontal Centrifugal Castings. C. Howson. (Foundry Trade Journal, 1946, vol. 78, Feb. 21, pp. 191–199). The formation of banded structures in centrifugal castings has been correlated with the degree of vibration of the casting machine in an earlier paper by L. Northcott and D. McLean (*see* Journ. I. and S. I., 1945, No. I., p. 303 P). In the present paper an effort is made to show that the existence of vibration is not a necessary condition, as in horizontal casting there is an inherent variation in mechanical force during rotation. The first section deals with mathematical and theoretical considerations with regard to centrifugal casting; some examples of ferrous and non-ferrous-metal centrifugal castings are described, and finally an attempt is made to explain the macrostructural formations encountered.

Centrifugally Cast Aircraft Parts. J. F. B. Jackson. (Aircraft Production, 1945, vol. 7, Nov., pp. 511–513). The application of the centrifugal casting process to irregular and asymmetrical units in high-tensile alloy steel is described, and the results of typical mechanical tests on centrifugal castings for aircraft are given.

Foundry Research at Watertown Arsenal. W. G. Gude. (Foundry, 1945, vol. 73, Dec., pp. 104–106, 186–188). A brief description is given of some of the research work on the centrifugal casting of steel gun-barrels which has been carried out at Watertown Arsenal in the United States.

Methods Employed to Obtain Rates of Solidification. K. L. Clark. (American Foundryman, 1945, vol. 8, Dec., pp. 24–25). This paper constitutes the first part of a report on work done by the Heat Transfer Committee of the American Foundrymen's Association. It describes tests in which a series of steel plates $6 \times 6 \times 2$ in., $8 \times 8 \times 4$ in., $12 \times 12 \times 6$ in., and $12 \times 8 \times 4$ in. were cast in dry-sand moulds and in chills. The flasks were overturned at selected time intervals after pouring, and the relationships between the thickness of the solidified skin and time were determined. The results obtained are given in tables, and in another part of the report (*see* next abstract) they are compared with those obtained using the heat-flow analysis developed by Paschkis (*see* Journ. I. and S. I., 1944, No. II., p. 267 P).

Studies on Solidification of Castings. V. Paschkis. (American Foundryman, 1945, vol. 8, Dec., pp. 26–37). This paper is the second part of the report on work done by the Heat Transfer Committee (*see* preceding abstract). Before the electrical analogy method can be used to attack heat-transfer problems in the solidification of castings, proof is required that the method is suitable. Data were therefore obtained by direct methods in the foundry, and these are compared in the present paper with data obtained with the mass-flow analyser. The electrical analogy method appears to be a promising tool, and it appears possible to establish with reasonable approximation one curve for sand casting and one for chill casting, showing the freezing times as functions of metal thickness. This approximation is better for smaller than for greater thicknesses.

PRODUCTION OF STEEL

(Continued from pp. 40 A–42 A)

Steel and the Engineer. A. Roebuck. (Journal of the Junior Institution of Engineers, 1946, vol. 56, Jan., pp. 93–96). The development of steelmaking in England is briefly reviewed, with notes on the work of eminent metallurgists and engineering achievements based on the use of steel.

Developments in the Iron and Steel Industry during 1945. W. H. Burr. (Iron and Steel Engineer, 1946, vol. 23, Jan., pp. 53–65). Progress made in the United States in 1945 in the production and finishing of iron and steel is reviewed.

German Toolsteel and Special Steel Industry. J. P.

Gill. (Metal Progress, 1946, vol. 49, Jan., pp. 122–124). A short account is given of the organization of the German tool-steel and special steel industry, with notes on the manufacturing practices.

The Production of Very Clean Steel in the Basic Bessemer Shop. J. Klärding. (Iron and Steel Institute, 1946, Translation Series, No. 268). This is an English translation of a paper which appeared in Stahl und Eisen, 1945, vol. 65, Mar. 1, pp. 118–121 (*see* Journ. I. and S.I., 1945, No. II., p. 35 A).

The Perrinisation of Basic Bessemer Steel in France. (Metallurgia, 1946, vol. 33, Jan., pp. 115–116). The Perrin steelmaking process, which was described by B. Yaneske (*see* Journ. I. and S.I., 1940, No. II., p. 35 P), underwent further development at Valençiennes in secret during the German occupation in the 1940–44 period, and a brief account of some of the work is given. It was found that practically pure iron could be produced by Perrinising basic-Bessemer steel with new aluminous slags. Normal basic converter steel at the end of the blow is slagged clean and a new basic slag put on. The steel is not over-oxidized. A ladle containing the aluminous slag is brought to a tapping position under the mouth of the vessel. The special slag, previously melted in an electric furnace, consists of lime and alumina; to prevent any phosphoric slag coming over in the tapping operation, lump lime is positioned at the mouth of the vessel to form a bridge. The vessel is then tipped quickly enough to give a rather violent intermixing action of the liquid slag and steel in the ladle. Additions of aluminium or ferrosilicon are made to the stream during tapping. The steel when cast into moulds is completely killed.

A Laboratory Investigation of the Phosphorus Reaction in the Basic Steelmaking Process. K. Balajiva, A. G. Quarrell, and P. Vajragupta. (Iron and Steel Institute, 1946, this Journal, Section I.). A new technique, developed for melting slags and metal together at controlled temperatures and for taking satisfactory samples of slag and metal, is described. The technique has been applied to a study of the phosphorus reaction at 1585° C., using prefused slags containing all the normal constituents except CaF_2, but with a much wider range of composition than is normally encountered in industry. It is shown that the empirical relationships which have previously been developed for purposes of industrial slag control break down when applied to slags having a wide range of compositions. On the other hand, a linear relationship is found to exist between the logarithm of the phosphorus equilibrium constant

$$\left(k = \frac{(P_2O_5)}{[P]^2\,(FeO)^5}\right)$$

and the logarithm of the total lime content of the slag. On the basis of this relationship, curves are drawn to assist in slag control at 1585° C.

X-ray and petrographic examinations of the slags have been carried out and three constituents have been identified: (1) A solid solution of $3CaO.P_2O_5$ in $2CaO.SiO_2$, (2) $2CaO.Fe_2O_3$, possibly in solid solution with $4CaO.Al_2O_3.Fe_2O_3$, and (3) an oxide phase consisting mainly of FeO, MgO, and MnO in solid solution. The free-lime contents of the various slags are calculated on the basis of $3CaO.P_2O_5$ and $2CaO.SiO_2$ and various assumptions with regard to Fe_2O_3 and Al_2O_3, and the correlation between log (free lime) and log k are determined statistically. Of the assumptions made, that in which Al_2O_3 was ignored and each molecule of Fe_2O_3 required 0·75 molecules of CaO, was found to give the best result, subject to the limitations involved.

The results of this preliminary investigation indicate that the new technique should be applicable to a wide range of slag-metal problems involved in the steelmaking process.

A Completely Automatic Control of Open-Hearth Reversal. B. M. Larsen and W. E. Shenk. (American Institute of Mining and Metallurgical Engineers, Technical Publication No. 1830: Preprint, Feb., 1945). A completely automatic system of reversal-valve control for open-hearth furnaces, operated by radiation pyrometers, is described.

The Occurrence of Oxygen in Liquid Open-Hearth Steel—Sampling Methods. T. E. Brower and B. M. Larsen. (American Institute of Mining and Metallurgical Engineers, Technical Publication No. 1868: Preprint, 1945). The differences in the results of oxygen analyses made from samples of steel taken: (*a*) by different sampling methods, (*b*) at different levels and positions in the bath, and (*c*) from the bath and pouring stream, were studied. Spoon-sampling when carefully carried out is considered preferable to immersing a small mould fitted with a sheet-metal cover in the steel bath by means of a long handle. The oxygen content of liquid steel in a finished heat is substantially the same all over the bath at the same level, but the content tends to decrease at increasing depths.

Electrolytic Manganese in Stainless-Steel Tests at Rustless Steel Corp. and Universal-Cyclops Steel Corp. (United States Bureau of Mines, Oct., 1945, Report of Investigations No. 3829). Tests are described which were carried out at two works making stainless steel rather high in manganese, in order to determine whether electrolytic manganese (about 99·95% purity) could be used in place of low-carbon 80–84% ferromanganese. The electrolytic manganese was produced at the pilot plant of the Bureau of Mines at Boulder City. Both works reported that the use of this material was advantageous in that closer control of the carbon and phosphorus contents was possible whilst the hot-workability, quality, and performance of the steel produced were unaffected.

Electrolytic Manganese in Acid-Steel Tests at Atlas Steel Castings Co. and the Detroit Steel Casting Co. (United States Bureau of Mines, Nov., 1945, Report of Investigations No. 3830). Industrial-scale tests have proved that electrolytic manganese is entirely satisfactory as the form of manganese for making additions to both open-hearth and electric furnace heats of acid steel in the low- and medium-carbon ranges. The proportion of manganese lost was no greater than is the case with ferromanganese.

Production of Nickel and Chrome Steels from Laterite Ores. T. F. Baily. Electrochemical Society, Oct., 1945, Preprint No. 29). Experiments using the electric-arc furnace for the selective reduction of the

laterite nickel-chromium-iron ores of Cuba are described. The principle applied in the experiment was that nickel oxide is more readily reduced than iron oxide, and iron oxide more readily than chromium oxide. Tests showed that only the nickel oxide, part of the iron oxide, and none of the chromium oxide were reduced. The process developed offers commercial prospects where the cost of electric power is low and other favourable conditions obtain.

Composite Steel. (Iron and Steel, 1946, vol. 19, Feb., pp. 57–60). A description is given of the high-frequency electric-furnace plant installed by James Neill and Company (Sheffield), Ltd., for making special steels. There are three furnaces with capacities of 2, 3, and 5 cwt., respectively. Special split moulds with a removable partition down one corner have been devised. High-carbon or alloy steel is first poured into the smaller mould; when this has solidified but is still white hot, the partition is removed, and the remainder of the mould is filled up with soft low-carbon steel. A composite ingot is thus obtained which, when rolled, machined and heat-treated, makes excellent cutting tools.

Stainless Steel Scrap. L. F. Weitzenkorn. (Blast Furnace and Steel Plant, 1945, vol. 33, Dec., pp. 1511–1512, 1537, 1538). A list is given of the American Iron and Steel Institute types and analyses of twenty-nine stainless steels; the value of stainless steel scrap and the necessity for careful segregation of the different types are emphasized.

Scrap-Handling Magnet Improved through Welded Design. (Steel, 1946, vol. 118, Feb. 4, pp. 134–136). Two modifications which improved the efficiency of a magnet for lifting scrap are described. One consisted of closing the gap between the pole ring and the housing, and the other of welding a special central pole shoe to the housing, the shoe being designed to withstand impacts when the magnet is lowered on to the scrap.

Novel Test Sample Speeds Tap Carbon Analysis. (Steel, 1946, vol. 118, Jan. 28, p. 148). A novel casting-pit sampling procedure is described. It consists of taking a test spoonful of slag-free metal from the bath, killing the steel with aluminium wire and drawing a column of approximately 6 in. of clean steel into a 6-mm. pyrex glass tube by suction with a rubber bulb. The sample is quenched in water; the glass is broken away and a sample $\frac{3}{4}$ in. long is sheared from the centre of the rod with clippers.

Progress with Large Electric Steel Furnaces. A. G. Arend. (British Steelmaker, 1946, vol. 12, Jan., pp. 34–37). Advancements in electric-furnace steel-making are reviewed, the subjects dealt with including electro-hydraulic control, making electrode material above the furnace and feeding it continuously through the furnace roof, and rapid charging with baskets.

Steel Production and Its Problems. D. Clark. (Australian Institute of Metals: Australasian Engineer, 1945, Dec. 7, pp. 41–52). A detailed account is given of the production of steel in the arc furnace, the heat-treatment of alloy and high-speed steel, induction hardening, and nitriding. Fatigue, corrosion-fatigue, and the differences between research and investigation are dealt with.

Manufacture of Steel Products from Billet-Size Ingots. R. W. Scholl. (Steel, 1946, vol. 118, Jan. 21, pp. 88–89, 104–108). A description of the steel-making practice at the Connors Steel Co., Birmingham, U.S.A., is given. Steel is made in two electric-arc furnaces with capacities of 3 and $4\frac{1}{2}$ tons/hr. respectively. Small ingots with a maximum size of about $5 \times 5 \times 60$ in. are cast and then rolled into finished products without any necessity for reheating.

Co-Operative Research in the Iron and Steel Industry. C. F. Goodeve. (Sheffield Society of Engineers and Metallurgists: Iron and Coal Trades Review, 1946, vol. 152, Mar. 15, pp. 501–502). The objects and scope of the recently formed British Iron and Steel Research Association are explained. One of its primary objects is to provide a mechanism whereby the brains of the people in the industry could be applied to the benefit of the whole of the industry as well as to that of the particular firm in which they worked. There was, and would continue to be, a Corrosion Testing Station to act as a centre of field investigations in that subject. It was planned to set up a Coatings Research Station at Swansea to specialize in all problems concerned with metallic and other inorganic coatings on steel.

REHEATING FURNACES

Pit Furnaces at Lukens. H. S. Hall. (Iron and Steel Engineer, 1945, vol. 22, Oct., pp. 81–85). An illustrated description is given of an installation of eight soaking-pits at the works of the Lukens Steel Company. Four pits are 15 ft. 9 in. $\times$ 10 ft. 6 in., and four are 12 ft. $\times$ 10 ft. 6 in., all with a depth of 11ft. 9 in.

Ingot Heating with Modern Soaking Pits. N. W. Richardson. (Iron and Steel Engineer, 1946, vol. 23, Jan., pp. 96–100). The descriptions are given of the following modern types of soaking pits: (1) The one-way-fired recuperative pit; (2) the bottom-fired recuperative pit; (3) the end-fired rectangular recuperative bed; and (4) the circular pit with burners placed tangentially round the bottom.

The Instrumentation of Soaking Pits. J. P. Vollrath. (Blast Furnace and Steel Plant, 1945, vol. 33, Nov., pp. 1391–1393). Descriptions and diagrams are given of electrical and other instruments for measuring and controlling the temperature of soaking pits, the temperature distribution, the pressure, the fuel flow, the gas/air ratio, and for signalling when the soaking process is finished.

Auxiliary Machinery for Ironworks Driven by High-Pressure Oil. M. Oledal. (Teknisk Tidskrift, 1945, vol. 75, Oct. 20, pp. 1139–1144). (In Swedish). Illustrated descriptions are given of charging machines operated by high-pressure oil for putting ingots in reheating furnaces.

FORGING, STAMPING, AND DRAWING

(Continued from pp. 42 A–43 A)

Quality Control of Truck and Bus Forgings. D. A. Barnes. (Steel Processing, 1945, vol. 31, Dec., pp. 760–762). The sequence of processes in the forging of parts of the steering mechanism for heavy motor vehicles in nickel–chromium–molybdenum steel is described and illustrated.

Upsetting Cylinder Barrels. G. W. Birdsall. (Steel, 1945, vol. 117, Dec. 31, pp. 53–56). A description is given of the sequence of processes by which marine engine cylinders about 8 in. in dia. are upset-forged in only four passes from solid blanks with a great saving in machining as compared with former methods.

Photo-Grids. F. Hewlett. (Aircraft Production, 1945, vol. 7, Sept., pp. 425–427). A method of producing fine-lined grids on metal sheets is described. The grids are used for measuring the flow and stretch of metal in pressing and forging operations.

Die Rolling. H. F. Marquardt. (Iron and Steel Engineer, 1946, vol. 23, Jan., pp. 68–71). The manufacture of dies and the process of die-rolling are described in detail.

Forging Die Design. J. Mueller. (Steel Processing, 1945, vol. 31, Dec., pp. 774–776). A description is given of the dies used for forging the crankshaft for a very small petrol engine with a cylinder only $\frac{15}{16}$ in. in dia.

Mass Producing Rocket Projectiles at Westinghouse Plant. W. G. Miller. (Industrial Heating, 1945, vol. 12, Oct., pp. 1694–1700, 1800). The processes of heating, forming, heat-treating, and machining, at a large plant of the Westinghouse Electric Corporation where rocket projectiles are made in huge quantities, are described.

A Review of the German Spring Making Industry. (Wire Industry, 1946, vol. 13, Jan., pp. 33–34). A brief review of the spring industry of Germany is presented; it is based on a Combined Intelligence Objectives Sub-Committee Report by R. W. Cook, supplied by the Controller of Springs of the Ministry of Supply.

New Wire Drawing Machine. (Wire Industry, 1946, vol. 13, Jan., p. 37). A description is given of a new 16-die, dry cone wire-drawing machine for finishing wire of 42–50 S.W.G. in both ferrous and non-ferrous materials.

An Extension of Wire-Drawing Theory, with Special Reference to the Contributions of K. B. Lewis. R. Winstanley Lunt and G. D. S. MacLellan. (Journal of the Institute of Metals, 1946, vol. 13, Feb., pp. 65–96). A rigid analysis of the wire-drawing process through a conical die channel has been developed in a manner formally similar to that adopted by Lewis, but with the introduction of two new quantities. These quantities are: (1) The mean normal stress on the die-channel wall, $\bar{\sigma}_n$, and (2) the mean coefficient of friction, $\bar{\mu}$, between the wire and the die channel, the averaging being carried out with respect to the interfacial surface concerned. The derivation of the numerical values of the two quantities has been described for the case when the wire is fed in tension to the die, and when the reaction on the die seating falls linearly as this tension is increased. By comparing this rigid analysis with Lewis's theory, it is found that his use of $\bar{Y}$, the mean yield stress of the metal in the deformation zone of the die, in place of $\bar{\sigma}_n$, is inadmissible. It is also found that the quantity μ_L, which appears in his theory as the coefficient of friction, is only a numerical factor taking account of the difference between $\bar{Y}$ and $\bar{\sigma}_n$.

The Importance of Reduction of Area in the Evaluation of High Carbon Steel Wire for Cold Drawing Purposes. D. A. Sutch and B. L. McCarthy. (Wire and Wire Products, 1945, vol. 20, Dec., pp. 923–925; 962–963). It is shown that the reduction in area at fracture in the tensile test on patented steel wire is a valuable guide to the microstructure of the material and to its suitability for drawing to make high-quality wire.

Drawing Wire without Lime. H. L. Trembicki. (Wire and Wire Products, 1946, vol. 21, Jan., pp. 38–39). A pickling, washing, and coating process which leaves an excellent lubricant on the wire for subsequent drawing is described. The coating compound has good wetting properties and is of very low alkalinity. Its composition is not stated, but it is a better drawing lubricant than lime.

ROLLING-MILL PRACTICE

(Continued from p. 23 A)

Overload Protection for Mill-Type D.C. Auxiliary Motors. G. A. Moffett. (Iron and Steel Engineer, 1945, vol. 22, Dec., pp. 67–71). The author discusses in detail the operation of several types of overload relays, and their application, particularly to D.C. auxiliary motors in the rolling mill.

Cold Rolling. C. E. Davies. (Metallurgia, 1946, vol. 33, Jan., pp. 147–153). Recent progress in the design of rolling mills and in the cold-rolling practice of steel strip and sheets in Great Britain are reviewed.

Roll Manufacture and Application. A. E. Murton. (Iron and Steel Engineer, 1945, vol. 22, Nov., pp. 51–56). The author describes the types of rolls in common use in American rolling mills and briefly discusses their manufacture, and the rolling conditions for which each type is suitable.

Merchant Mill and Alloy Finishing Facilities at Fontana. R. M. Bickerstaff. (Blast Furnace and Steel Plant, 1945, vol. 33, Dec., pp. 1513–1522). A detailed description is given of the merchant bar mill

at the Kaiser Steel Plant, Fontana, California. It was put in commission in April, 1945, and is designed to roll flats up to 18 in. wide, rounds up to $4\frac{1}{2}$ in. in dia., squares up to 3×3 in., and angles up to 3×3 in. The mill has a capacity of about 180,000 tons per annum.

The Manufacture of Seamless Steel Tubes. J. W. Jenkin. (Sheffield Society of Engineers and Metallurgists: Metallurgia, 1945, vol. 33, Nov., pp. 3–6; Dec., pp. 59–64; 1946, Jan., pp. 139–144). Detailed and illustrated descriptions are given of various methods of manufacturing seamless steel tubes including the pilger, Diescher, Assel and Foren processes.

Seamless Steel Tubes. H. Sanders. (British Steelmaker, 1945, vol. 11, Nov., pp. 500–504; Dec., pp. 557–561). Descriptions are given of the processes involved in making "hollows" (the raw material for seamless steel tubes), the sinking and plug-drawing methods of reducing the hollows and the heat-treatment of the finished tubes.

Heavy Wall Pipe. E. C. Wright. (American Society for Testing Materials: Steel, 1945, vol. 117, Dec. 31, pp. 70–72). The difficulties and high costs involved in the rolling of thick-walled tubes which are only required in small quantities are discussed, and some suggestions for simplifying the specifications and reducing the costs are made.

Salvaging Forged Alloy Steel Rolls. H. L. Watson, jun. (Iron and Steel Engineer, 1945, vol. 22, Dec., pp. 55–60). The following methods of salvaging worn-out rolls are described and illustrated: Simple regrinding after normal use; repairing damaged rolls by grinding and etching; stress-relieving treatments; rehardening for use in the same mill; turning down into smaller rolls for use in another mill; renewing either forged or cast back-up rolls by shrinking-on a sleeve.

HEAT-TREATMENT

(Continued from pp. 43 A–45 A)

Heat Treating B-29 Super-Fortress Engine Parts in Mammoth Dodge-Chicago Plant. (Industrial Heating, 1945, vol. 12, Oct., pp. 1658–1690; Nov., pp. 1872–1878, 1900). An illustrated description is given of an extensive heat-treatment plant of the Chrysler Corporation. This comprises carburizing furnaces, a continuous gas-fired radiant-tube annealing furnace 60 ft. long, a nitriding plant, and continuous hardening and tempering furnaces. The heat-treatment plant for making and maintaining the tools for the above operations are described in the second part of the article.

Fabricating and Heat Treating Hollow Steel Propeller Blades at Curtiss-Wright Plant. (Industrial Heating, 1945, vol. 12, Oct., pp. 1702–1716; Nov., pp. 1888–1900). The equipment and processes used in the manufacture of hollow steel propeller blades for aircraft are described. This involves milling and blanking the plates with subsequent pressing, shaping, welding, brazing, and heat-treatment.

Grinding Hardened Steel Precision Gears. E. A. Koether. (Engineering Materials and Processing Methods, 1945, vol. 22, Dec., pp. 1754–1758). The heat-treatment and finishing of gears for aero-engines are discussed with special reference to the effects of grinding, decarburization and shot-peening on the fatigue strength.

Temperature-Time Distribution in Rectangular Bars. W. M. Rohsenow, M. J. Aronstein, and A. C. Frank. (Transactions of the A.S.M.E., 1946, vol. 68, Feb., pp. 135–141). Charts for determining the changes of temperature with time in the heating of flat plates, infinite cylinders, and spheres have been published previously. In this paper the lower ends of these curves are amplified. In addition, the rapid convergence of the series solution is shown, and series of curves for rectangular bars are presented.

Gaseous Cementation. J. Pomey. (Laboratoire des Usines Renault, Billancourt, Paris, Dec. 18, 1942). A comprehensive report on the gas-carburization of steel is presented in four parts. In Part I. the history and present state of development of the process are reviewed and the equilibria between iron, austenite and cementite on the one hand, and CO-CO_2 mixtures and the hydrocarbon gases on the other hand, are dealt with. In Part II. an account of laboratory experiments with gas-carburizing is given. In Part III. the preparation of a suitable carburizing gas and the control of its temperature, pressure and composition by methods developed at the Usines Renault are described; this gas consists of charcoal producer gas with an addition of propane. In Part IV. a small rotating chamber for carburizing small parts in batches and a large continuous furnace equipped with a pusher for dealing with plates are described.

Summary of a Study of Gaseous Cementation. J. Pomey. (Laboratoire des Usines Renault, Billancourt, Paris). The equilibria involved in gas-carburizing are studied and the plant developed at the Usines Renault for preparing the gas and carburizing small parts and plates is described. This process has been found to cost less than half as much as box-carburizing with a solid medium.

Characteristics and Uses of Salt Baths. R. C. Stewart. (Iron Age, 1946, vol. 157, Feb. 14, pp. 46–52). The development of salt baths with submerged water-cooled electrodes has given new impetus to the use of salt baths in the mass-production heat-treatment of both ferrous and non-ferrous metals. In this paper a review is presented of these and other improvements in cyanide and carburizing baths, with notes on the composition of the solutions used.

The Isothermal Heat-Treatment of Steel. E. F. Watson and J. McArthur. (Machinery, 1946, vol. 68, Feb. 28, pp. 265–271). The isothermal heat-treatment of steel is explained by reference to the S-curve. The equipment required and the properties of the molten salt for quenching are discussed, and the

results obtained by this treatment in the hardening of rocket tubes, knife blades, machete blades, and pistol parts are given. The principal advantages of the treatment are the reduction in distortion and the fact that finished-machined parts can be hardened.

Precise Control of Steel Hardening. H. A. Knight. (Engineering Materials and Processing Methods, 1945, vol. 22, Dec., pp. 1736–1738). A brief description is given of the heat-treatment furnaces, the process, and the methods of control which were developed for hardening 24½-in. bars, tapering from ¾ in. to 1¼ in. in dia., of chromium–molybdenum steel.

Effect of Preliminary Treatment on High-Speed Steels. F. F. Dodson. (Metallurgia, 1946, vol. 33, Jan., p. 124). The sodium-cyanide treatment for high-speed steel described by J. McIntyre (*see* Journ. I. and S.I., 1945, No. I., p. 50 A) is discussed and some experiments on 18%-tungsten and 6%-molybdenum high-speed steels are described. It was confirmed that the treatment does slightly enhance the hardenability for a certain depth, but does not increase the total hardenability.

Flame-Hardening in the Small Shop. W. B. Sharav. (Welding Journal, 1946, vol. 25, Jan., pp. 19–24). A number of designs of flame-hardening equipment for use in small workshops are described and illustrated.

Flame-Hardening Small Machined Parts. (Iron Age, 1946, vol. 118, Feb. 7, p. 77). A flame-hardening machine for parts between 1½ and 12 in. in dia. is described. The part to be hardened is spun on a vertical axis and heated by a number of radially positioned oxy-acetylene burners. On attaining the correct temperature the burners are withdrawn and sprays of water are directed on the part.

Induction Hardening as Applied to Farm Machinery. F. F. Vaughn. (S.A.E. Journal, 1946, vol. 54, Jan., pp. 38–43). Problems involved in induction-hardening are reviewed and some examples of the successful application of induction-hardening to parts of agricultural machinery are described.

Induction Heating. N. R. Stansel. (Iron and Steel Engineer, 1946, vol. 23, Jan., pp. 102–111). The principles of induction heating are explained and data which enable the heating rates of different sizes and shapes of bar to be calculated are presented.

Induction Heating for Shrinking-On Heavy Parts. (Machine Shop Magazine, 1946, vol. 7, Feb., pp. 45–46). Descriptions are given of two induction-heating machines made up from components of resistance-welding machines. The former were used for rapidly heating up 50-lb. steel suspension arms for shrinking on to spindles.

Nitriding of Aircraft Steels. P. A. Haythorne. (Iron Age, 1946, vol. 157, Jan. 31, pp. 44–48). An investigation is described in which the surface hardness and changes of hardness with depth obtained on nitriding the following steels at 900°, 950°, and 1000° F. in 30%, 45%, and 60% dissociated ammonia, respectively, were studied : (1) A 0·19%-carbon steel, (2) a 0·95%-carbon steel, (3) a 0·91%-chromium 0·22%-molybdenum steel, (4) three chromium–nickel–molybdenum steels, and (5) Nitralloy G (containing 1·33% of chromium, 0·33% of molybdenum, and 1·30% of aluminium). The results are presented as depth-hardness curves. The acceptance of nitrided steels on the basis of surface hardness alone is not generally justified, although this value may serve as a basis for comparison.

Cycle Annealing of Hypo-Eutectoid Steels. G. R. Brophy. (Iron Age, 1945, vol. 156, Dec. 13, pp. 69–71). The austenite in some complex alloys is so slow to transform during continuous cooling that many days are required to soften them adequately for machining and cold-working. A method of heat-treatment is outlined which reduces the time of treatment.

The Application of Cathode-Ray Oscillographs when Photographing Cooling Curves for Quenching Oils. B. Levy. (A/B. Wahlén och Block, Wabo Tekniska Meddelanden, 1945, No. 3, pp. 1–6). (In Swedish). A description is given of an apparatus which was set up for obtaining permanent records of the cooling curves for quenching oils obtained with a cathode-ray oscillograph.

The Resistance of Quenching Oils to Oxidation. (A/B. Wahlén och Block, Wabo Tekniska Meddelanden, 1945, No. 3, pp. 6–8). (In Swedish). A description is given of a simple appartaus for determining the rate at which quenching oils absorb oxygen. The stability of an oil is greatly reduced by an organic compound, ferric naphthenate, which forms after the oil has been used a few times. Rust also reduces the resistance to oxidation, but to a less extent. The use of oxidation inhibitors is discussed.

WELDING AND CUTTING

(Continued from pp. 45 A–47 A)

Economics of Arc Welding. W. J. Brooking. (Steel, 1946, vol. 118, Jan. 21, pp. 81, 111, 112 ; Jan. 28, pp. 124–126, 187–189). The costs of electric welding are analysed and several important factors affecting the costs are discussed.

Arcwelding Trends in Wartime Germany. F. W. Myers, jun. (Iron Age, 1946, vol. 118, Feb. 7, pp. 56–60). The measures which were taken in Germany during the war to meet the increased demands on the welding industry are outlined. No very important developments are cited, but some interesting work was done in the production of welded passenger coaches, frameless tank cars, and mine tubs.

Metallurgy as Applied to Welding. R. B. Lincoln. (Welding Journal, 1945, vol. 24, Dec., pp. 1143–1147). The metallurgical characteristics of carbon steels and alloy steels which affect its welding properties are explained. If electrodes of 14%-manganese steel are used to deposit a hard face on plain carbon steel there will be a layer, somewhere between the parent metal and the surface, where the composition is 3–5% of manganese and this will be hard and brittle. This

can be avoided by depositing an intermediate layer of 18/8 stainless steel.

Metallurgical Features in Welded Steels. H. O'Neill. (Transactions of the Institute of Welding, 1946, vol. 9, Feb., pp. 3–9). The conditions affecting the weldability of high-tensile steels are reviewed. A progress report is given on the new simple weld ductility test. From a study of the welding of steel both in the primitive smith's hearth and by modern non-fusion processes a critical definition of the art is suggested. This definition would distinguish in principle between bonding effects due to true welding and adhesion effects such as those which occur between loaded metallic surfaces in rubbing contact. The fusion welding of ordinary steels is considered next with particular reference to the curious local hardening produced in ferrite by "stray flashes". Wöhler fatigue tests on a low-alloy steel intentionally provided with these hard spots have indicated the danger of such isolated arc craters in structures subjected to dynamic stresses.

Selection of Steel for Welding. S. L. Hoyt. (Welding Journal, 1945, vol. 24, Dec., pp. 1180–1187). Factors affecting the selection of steel for welding are discussed with special reference to steels for oil-well casings and shipbuilding.

Arc Welding at the Newcastle Steel Works. A. Young. (B. H. P. Review, 1945, vol. 23, Dec., pp. 18–19). Examples of the electric welding for construction and maintenance at the Newcastle Steel Works of Broken Hill Proprietary Co., Ltd., are described and illustrated.

The Quantitative Measurement of Welding Response by Bead Welds. R. D. Stout, S. S. Tör, and G. E. Doan. (Welding Journal, 1945, vol. 24, Dec., pp. 625-S–628-S). In the system for predicting the ductility of welds developed at Lehigh University, the Jominy end-quench test was used to measure the response of the steel to welding. This is an indirect method of measurement. In this paper a direct method is proposed. A series of welds are made by depositing a bead on each of a number of plates, using a different rate of heat input each time. Hardness traverses are made on each. By applying a "geometry factor" to the hardnesses measured for the various rates of heat input it is then possible to predict the heating rates which would produce the desired hardness in a weld of different design.

The Welding of Nickel-Alloy Steels. T. N. Armstrong. (Iron Age, 1946, vol. 157, Jan. 24, pp. 36–41; Jan. 31, pp. 49–55; Feb. 7, pp. 69–76; Feb. 14, pp. 56–60). In the first part of this series of articles the factors influencing the weldability and tests for the weldability of nickel steels are dealt with. In the second part weldability tests, including the T bend test, the single V-groove weld test, and the Reeve cracking test, and tests for selecting welding electrodes are described. In the third part structural welding and the welding of pressure vessels are dealt with. In the fourth part descriptions are given of spot-welding, upset butt-welding, forge welding, oxy-acetylene welding, and oxy-acetylene pressure welding.

Welding of Nitralloy Steels. D. Llewellyn. (Welding, 1946, vol. 14, Feb., pp. 70–73). The results obtained from hardness, tensile and impact tests on welded specimens of low-alloy chromium–nickel–molybdenum steels to British Standard Specifications En 40 and En 41 are presented and different methods of welding these Nitralloy steels are discussed. The atomic hydrogen welding process is the most satisfactory; oxy-acetylene welding gives four results, and metallic-arc welding is satisfactory provided that suitable electrodes are used.

Resistance Welding on Stainless Steel Aircraft Engines and Accessories. F. G. Harkins and W. L. Hales. (Welding Journal, 1946, vol. 25, Jan., pp. 39–46). Descriptions are given of methods adopted for the resistance-welding of complicated stainless-steel parts for aircraft engines.

Resistance Welding. Part I. Modern Developments and Applications in Up-to-Date Fabrication Methods. Part II. Equipment for Spot Welding Light Alloy Material: Stitch and Projection Welding. Part III. A Survey of the Seam Welding Process and Equipment. R. W. Ayers. (Aircraft Production, 1945, vol. 7, Aug., pp. 379–384; Sept., pp. 446–450; Oct., pp. 490–494). A comprehensive and profusely illustrated review of the latest types of spot- and seam-welding machines for both ferrous and non-ferrous metals is presented and the principles employed are explained.

Measurement of the Effect of Contact Resistance in Spot Welding. R. A. Wyant. (Electrical Engineering, 1946, vol. 65, Jan., pp. 26–33). A description is given of an apparatus for measuring the electrical contact resistance in the spot-welding of sheet metal. The results of resistance tests in the spot-welding of aluminium-clad steel sheet are presented and discussed.

Quality Control and Spot Welding. N. G. Dod. (Aircraft Production, 1945, vol. 7, Dec., pp. 563–564). The application and value of statistical methods in controlling the quality of spot welds are discussed.

Testing Welds in Holland. (Institute of Welding: Metallurgia, 1946, vol. 33, Jan., p. 145). A brief account is given of a co-operative organization which the shipbuilding and engineering industries of Holland have set up for making X-ray examinations of welded structures of all kinds, particularly for shipbuilding.

Controlling Distortion in the Gas Welding of Sheet Metals. C. G. Bainbridge. (Sheet Metal Industries, 1946, vol. 23, Feb., pp. 356–362). The causes of distortion in the gas-welding of sheet metal are analysed. The correct preparation of butt, corner, lap and T joints and the appropriate welding procedure are described, and details of jigs for particular jobs are given.

How to Select and Use Cast Iron Shanks for Cutting Tools. (Steel, 1946, vol. 118, Jan. 14, pp. 90–91, 124–126). A description is given of the making of cutting tools by brazing high-speed-steel or tungsten-carbide tips to shanks of high-strength cast iron.

Modern Hard-Facing Methods. A. R. Lytle. (Welding Journal, 1945, vol. 24, Dec., pp. 1155–1165). Illustrated descriptions are given of the equipment and techniques for welding a layer of abrasive and/or heat-resistant alloys on to the wearing surface of steel bars, cylinders, seating rings, and gears.

Unusual Flame Cutting. (Welding, 1946, vol. 14, Jan., pp. 40–42). Descriptions are given of the oxy-

acetylene cutting of nickel–chromium–molybdenum steel 44 in. and 54 in. thick. A test was also made on mild steel 60 in. thick which demonstrated that it was a practical proposition with the $\frac{1}{4}$-in. dia. nozzle employed. Details of the cuts, the equipment used, and the oxygen consumption are given.

Flame Cutting. J. F. Smythe. (Steel, 1946, vol. 118, Jan. 14, pp. 104, 131). An 8-torch electrically controlled flame-cutting machine was developed for the mass production of breech blocks. A description of the machine is given.

Cost Reduction Aspects of Flame-Cutting Operations. G. V. Slottman. (Machinist, 1946, vol. 89, Feb. 16, pp. 2392–2395). Methods of increasing production and decreasing costs when using multiple-burner oxy-acetylene cutting machines are described and illustrated.

PROPERTIES AND TESTS

(Continued from pp. 50 A–54 A)

The Effect of Triaxiality on the Technical Cohesive Strength of Steels. G. Sachs and J. D. Lubahn. (American Society of Mechanical Engineers : Welding Journal, 1946, vol. 25, Jan., pp. 53-S–63-S). The fundamental characteristics of metals revealed by means of extensive tensile tests on notched bars are described. The effects of the three major factors, triaxiality, plastic strain, and stress concentration, can be separated by means of systematic tests covering the dependence of the strength of notched bars upon such variables as notch radius, notch depth, and hardness. The characteristic strength values obtained by tensile tests on notched bars appear to be of considerably greater practical significance than those obtainable by means of the conventional tensile test.

Cold Heading Die Steel. A. S. Jameson. (Steel, 1946, vol. 118, Jan. 21, pp. 82–85, 123–126). Data on the hardness, hardness depth, and grain size of high-carbon and low-alloy steels for cold-heading dies are presented and discussed.

The Fabrication of High-Strength Steel. C. E. Loos. Steel Processing, 1945, vol. 31, Dec., pp. 755–759). The hot- and cold-working properties of two high-strength steels, namely, " Cor-Ten " and a structural carbon steel are compared.

The Effect of Various Elements on the Hot-Workability of Steel. H. K. Ihrig. (American Institute of Mining and Metallurgical Engineers, Technical Publication No. 1932 : Metals Technology 1945, vol. 12, Oct.). A quantitative hot-workability test has been devised to determine the effect of various elements on the hot-workability of steels. The following elements had little or no effect : Oxygen, carbon, phosphorus, cobalt, vanadium, and titanium. The following elements had a beneficial effect : Manganese, nickel, and chromium (above 9%). The following elements had a detrimental effect : Sulphur, selenium, silicon, nitrogen, molybdenum, columbium, lead, tin, and chromium (below 9%).

Effect of Heat Treatment on the Endurance Limit of Alloyed Gray Cast Iron. T. E. Eagan. (American Foundryman, 1945, vol. 8, Dec., pp. 44–53). Tests were carried out to determine whether nickel–molybdenum cast iron could be heat-treated so as to obtain sufficiently high endurance limits for the material to be used for making crankshafts. The results indicated that, in general, heat-treatment to obtain a high tensile strength does not increase the endurance limit in proportion. The original as-cast structure has a profound influence on the endurance limit obtained after heat-treatment. Nickel–molybdenum and nickel–chromium–molybdenum grey cast irons with not much free cementite present can be heat-treated to give an acicular structure with an increase in the endurance limit.

Addition Method of Calculating Rockwell C Hardness of the Jominy Hardenability Test. W. Crafts and J. L. Lamont. (American Institute of Mining and Metallurgical Engineers, Technical Publication No. 1928 : Metals Technology 1945, vol. 12, Oct.). A method of calculating the hardness of alloy steel in Rockwell C units is described. A basic hardness number corresponding to that of a pure iron-carbon alloy cooled at a certain rate is taken, and to this increments of hardness, corresponding to the amounts of alloying elements present, are added. The validity of the calculation of the hardness was confirmed by data obtained on standard qualities of steel and the accuracy is sufficient for the method to be useful in predicting and controlling hardenability.

An Appraisal of the Factor Method for Calculating the Hardenability of Steel from Composition. G. R. Brophy and A. G. Miller. (American Institute of Mining and Metallurgical Engineers, Technical Publication No. 1933 : Metals Technology 1946, vol. 12, Oct.). Grossmann's method of calculating the hardenability of steel from its composition is critically reviewed. A number of tests are described in which the effect of nickel, manganese, chromium and molybdenum on the hardenability of steel were determined, and the data obtained are compared with the hardenabilities predicted by the above method.

Supersonic Testing in a Steel Plant. J. V. Russell and H. E. Pellett. (Iron Age, 1946, vol. 157, Jan. 31, pp. 38–43). A description is given of the Sperry supersonic reflectoscope for detecting flaws in billets and blooms up to 20 in. square. The presence and position of defects are determined by measuring the difference in the times at which reflections of waves of supersonic frequency transmitted from one side of the billet are received from the opposite surface and from the defect.

The Detection of Cracks in Steel by Means of Supersonic Waves. C. H. Desch, D. O. Sproule, and W. J. Dawson. (Iron and Steel Institute, 1946, this Journal, Section I.). In Part I. previous methods of detecting flaws in steel by means of sound waves, especially those of high frequency, are reviewed. In Part II. a description is given of an apparatus employing piezo-electric quartz transmitters for pro-

ducing intermittent pulses of supersonic waves, and receiving them on similar quartz crystals after reflection, the reflected waves being electrically amplified and indicated on a cathode-ray oscilloscope. The conditions for obtaining sharp indications are discussed, as well as the effects of the degree of finish of the metallic surfaces under examination. In Part III. are given the results of applying the new method in works practice, including those obtained with large masses, billets, plates, castings, and welds. The conditions necessary for the satisfactory use of the apparatus for practical testing are discussed. It is maintained that supersonic testing should be regarded primarily as a new instrument of investigation, giving information which cannot at present be obtained by more usual methods.

Supersonic Inspection. (Steel, 1945, vol. 117, Dec. 24, pp. 94–96). A description is given of the " Hypersonic Analyser " for the detection of minute defects in steel. The instrument is capable of transmitting wave frequencies in the 50–1000 kilocycle range.

Magnetic Analysis Inspection of Metals. H. L. Edsall. (Engineering Materials and Processing Methods, 1945, vol. 22, Dec., pp. 1731–1735). Examples are given of the application of electronics to detect defects in steel bars and tubes by irregularities in their magnetic properties.

Sorting Metals by Tribo-Electrification. A. Doscheck. (Steel, 1945, vol. 117, Dec. 24, pp. 106–110). An electrical method of sorting metals is described. It is based on the measurement of the potential produced when the specimen of unknown origin is made to vibrate against a reference specimen. If the specimens are identical no potential is produced, but if they are different, the millivoltage and the polarity are indicative of the differences in composition or structure.

Fracture Phenomena in Steels at Elevated Temperatures. C. Schaub. (Jernkontorets Annaler, 1946, vol. 130, No. 1, pp. 1–26). (In Swedish). After reviewing several recent papers on creep tests, particularly on the types of fracture obtained in creep tests, an account is given of investigations carried out in 1942–1944 at the Kungl. Tekn. Högskolans institution för hållfasthetslära in Stockholm. In order to obtain a complete picture of the behaviour of steel at high temperature the usual creep-test should be supplemented by impact tests after long-time annealing and by long-time tensile tests on notched specimens. A stable material should have no embrittlement tendency and there should be no tendency to form cracks similar to stress-corrosion cracks. Tests with a 0·7%-chromium 3·25%-nickel 0·65%-molybdenum steel showed that, by raising the chromium content at the surface to about 30%, the life of the steel at high temperatures was increased and there was no tendency to crack formation.

Graphitization of Carbon–Molybdenum Steel in High-Temperature Steam Piping. G. A. Timmons. (American Society of Mechanical Engineers: Welding Journal, 1946, vol. 25, Jan., pp. 1-S–6-S). Graphitization of carbon-molybdenum steel tubes in high-temperature steam installations is considered from the viewpoints of thermodynamic stability and rates of reaction. Cementite is not stable below 1490° F. but graphite is, so that graphitization may be expected whenever cementite is present in a steel placed in service at 850–1000° F. Factors which accelerate graphite nucleation lengthen service life. By restricting the carbon content to less than 0·06% and providing alloying elements to give adequate creep strength it should be possible to produce steel suitable for high-temperature steel tubes. A complex carbide $(FeMo)_{23}C_6$ may be produced in a low-carbon 0·50%-molybdenum steel by the isothermal transformation of austenite at 1300° F. Some creep-test data for iron alloys containing 0·50% of molybdenum and less than 0·05% of carbon are presented.

Opinions on Graphitization. L. Crome. (Foundry, 1945, vol. 73, Dec., pp. 102–103, 248–258). The mechanism of the formation and growth of graphite in cast iron and of the solution of graphite in white iron is explained and discussed.

METALLOGRAPHY AND CONSTITUTION

(Continued from pp. 54 A–55 A)

The Upright Type of Microscope in Metallography. J. R. Vilella. (Metal Progress, 1946, vol. 49, Jan., pp. 113–116). The merits of the inverted and upright types of microscope are discussed and micrographs of the same area of metallographic specimens taken with both types of instrument are compared.

A New Etching Reagent for the Detection of Oxygen Segregations in Steel. L. Fine. (Metal Progress, 1946, vol. 49, Jan., pp. 108–112). Details are given of the preparation of an alkaline chromate etching solution and examples are cited illustrating its successful use to detect and study segregated oxides in steel.

Grain Boundaries. R. C. Bernhoeft. (Metallurgia, 1946, vol. 33, Jan., pp. 117–120). The theories relating to grains and grain boundaries in the structure of metals, which have appeared in the literature since 1929 are reviewed and discussed.

Solid Solutions—Classification of the Solubilities of Elements in Iron. I. I. Kornilov. (Iron and Steel, 1946, vol. 19, Feb., pp. 52–56). This is a translation of a Russian paper which appeared in Izvestia Akademii Nauk S.S.S.R. The author studies the solubilities of elements in iron in the solid state from the point of view of Hume-Rothery's size-factor theory. He reviews the available information and shows that the size factor alone is adequate to account for the experimental results except in the case of cerium and certain elements of the B sub-groups of the fourth and fifth periods of the periodic system.

The Phase Changes of SAE 2345 Steel. A. Dubé and R. L. Cunningham. (Transactions of the Canadian Institute of Mining and Metallurgy, 1946, vol. 49, pp. 1–16). The mechanical properties of steel S.A.E. 2345 (a 3·5%-nickel steel) after quenching and

tempering at 1050°, 1150°, 1200°, and 1225° F. were studied. A hardening and embrittling effect on the steel was noted when the steel was tempered at temperatures higher than 1150° F. On holding the steel at temperatures somewhat below the Ac_1 point (1275° F.), as determined with a dilatometer, there was a decrease in the intensity of magnetization as well as in specific volume. X-ray diffraction technique revealed that the phase formed on holding at 1240° F. was austenite, and this austenite had a sluggish transformation behaviour.

CORROSION OF IRON AND STEEL

(Continued from pp. 55 A–56 A)

Developments in Corrosion Studies and Corrosion Control. H. M. Olson. (Iron and Steel Engineer, 1946, vol. 23, Jan., pp. 80–95). A review of the literature from 1935 to 1945 on corrosion studies is presented.

Some Notes on Corrosion in Cast-Iron Sectional Boilers. E. R. Walter. (Journal of the Institution of Heating and Ventilating Engineers, 1946, vol. 13, Jan.–Feb., pp. 285–292). The causes of the corrosion of low-pressure cast-iron sectional boilers are examined and suggestions for its prevention are made. To prevent the steam in the products of combustion from condensing, all parts of the heating surface must be maintained at a temperature above the dew-point. The return-water temperature should be raised by by-passing a portion of the hot outlet water into the return manifold.

Stress Corrosion Cracking of Mild Steel. Part II. The Accelerated-Precipitation Theory of Stress Corrosion. J. T. Waber and H. J. McDonald. (Corrosion and Material Protection, 1945, vol. 2, Dec., pp. 13–16). A general theory of stress corrosion has been developed. Contrary to previous conceptions the present theory states that the direction of crack growth depends upon the localized electrochemical condition which has been induced by the applied and residual forces.

Stress Corrosion Cracking of Mild Steel. Part III. Methods of Testing the Accelerated-Precipitation Theory. J. T. Waber, H. J. McDonald and B. Longtin. (Corrosion and Material Protection, 1946, vol. 3, Jan., pp. 13–19). The conditions which an alloy must satisfy in order to be susceptible to stress corrosion are set forth. These include that the alloy must be capable of strain-ageing and that one of the precipitated phases is anodic to the parent phase, the latter not being severely attacked by the corrosive environment. It is shown from thermodynamic considerations that Fe_4N is anodic to steel and can form $Fe(OH)_2$ rather than Fe_3O_4.

Reaction Rate of Hydrogen Chloride and Sulfide with Steel. C. F. Prutton, D. Turnbull, and G. Dlouhy. (Industrial and Engineering Chemistry, Industrial Edition, 1945, vol. 37, Nov., pp. 1092–1097). In investigations of the possible corrosive action of extreme pressure lubricants on gear teeth the rate of attack on iron and steel by hydrogen chloride, hydrogen sulphide, and mixtures of the two were carried out. At a pressure of 1 atm. the amount of reaction, y, of iron with hydrogen sulphide may be represented as a function of time, t, by the equation $y^2 = Kt + A$, where K is a constant depending upon temperature and pressure, and A is a constant which may be zero or have a positive value depending on the type of iron. Hydrogen chloride reacts much less rapidly with iron and steel than hydrogen sulphide. When a 1 to 1 mixture of the two reacts with steel, the rate of formation of iron chloride is about the same as when hydrogen sulphide is absent.

Total-Immersion Apparatus. M. Cohen. (Electrochemical Society: Steel, 1946, vol. 118, Jan. 14, p. 106; Iron and Steel, 1946, vol. 19, Feb., pp. 75–76). A description is given of an apparatus for making total-immersion corrosion tests in which the specimen is held in a glass tube connected by rubber tubing to two graduated flasks. One flask is kept stationary and the other is moved up and down by a motor-driven mechanism, thus causing the water, or other corroding medium, to flow backwards and forwards over the surface of the specimen.

ANALYSIS

(Continued from pp. 33 A–34 A)

Iron and Steel Analysis. E. C. Pigott. (Iron and Steel, 1945, vol. 18, Dec., pp. 641–645; 1946, vol. 19, Jan., pp. 7–12; Feb., pp. 61–62). Details are given of methods recommended by the author for determining the following elements in iron and steel: Aluminium, carbon, chromium, cobalt, copper, lead, manganese, molybdenum, nickel, phosphorus, silicon, sulphur and zirconium.

A Photoelectric Recording Polarograph. L. Lykken, D. J. Pompeo, and J. R. Weaver. (Industrial and Engineering Chemistry, Analytical Edition, 1945, vol. 17, Nov., pp. 724–728). The apparatus described is a convenient photo-electric recording polarograph for accurate analytical work; the polarograms are automatically traced on a moving chart in plain view of the operator.

Photoelectric Type Portable Photometers. (British Standards Institution, 1945, No. 667). This specification covers the requirements for portable photoelectric photometers in which the test surface embodies a rectifier photo-electric cell.

Evaluation of Spectrographic Analytical Data. H. V. Churchill and J. R. Churchill. (Industrial and Engineering Chemistry, Analytical Edition, 1945, vol. 17, Dec., pp. 751–754). The statistical treatment of data obtained by spectrographic analyses is

discussed. The magnitude of the standard deviations is in general no higher than would be expected had the comparisons been made among chemical analyses carried out by different routine analysts.

Semi-automatic Spectrographic Analysis. R. H. Zachariason. (Industrial and Engineering Chemistry, Analytical Edition, 1945, vol. 17, Dec., pp. 749–750). Semi-automatic devices are described which simplify spectrographic analyses by reducing considerably the time required for changing the plate after each exposure, focusing the electrodes, controlling the exposure, and changing the electrodes.

Spectrographic Analysis. J. Convey and L. G. Young. (Journal of the Birmingham Metallurgical Society, 1945, vol. 25, Sept., pp. 168–189). Current literature indicates that instability of the source of light and insufficient reproducibility of spectral excitation used by different experimenters are the main difficulties which to-day retard the development of applied spectrography. In this paper spectrographic excitation sources are discussed and methods of stabilizing spectral emission are described.

Spectrochemical Determination of Small Amounts of Aluminium in Steel. R. Spiers, P. Fischer, and K. L. Proctor. (Industrial and Engineering Chemistry, Analytical Edition, 1945, vol. 17, Dec., pp. 772–774). A spectrochemical method is described for the determination of aluminium in steel samples weighing from 0·020 to 0·500 g. Colorimetric procedures proved to be unsuitable because of the presence of interfering ions. In the method developed, a mercury cathode separation is employed and one drop of the aluminium solution, prepared by the chemical procedure described, is placed on each of the flat-topped carbon electrodes which are sparked for 75 sec. immediately after the solution has been absorbed.

Spectrophotometric Determination of Titanium in Steels. A. Weissler. (Industrial and Engineering Chemistry, Analytical Edition, 1945, vol. 17, Dec., pp. 775–777). Absorption spectra have been determined for the hydrogen-peroxide complexes of titanium and vanadium in the presence of 1 g. of iron, in perchloric-phosphoric acid solution. These spectra furnish the basis for improved rapid and accurate methods for the determination of from 0·5 to 6 mg. of titanium in iron, steel, vanadium steel, and stainless steel, without separating the titanium or using hydrofluoric acid.

Rapid Method for Determination of Copper in Steel. F. B. Clardy, J. C. Edwards, and J. L. Leavitt. (Industrial and Engineering Chemistry, Analytical Edition, 1945, vol. 17, Dec., pp. 791–792). A method is described for the rapid and accurate determination of copper in plain and alloy steels for foundry control. The total time required is approximately 15 min.

The Spectrochemical Determination of Metallic Impurities in Steel. C. G. Carlsson. (Iron and Steel Institute, 1946, Translation Series, No. 267). An English translation is presented of a paper which appeared in Jernkontorets Annaler, 1945, vol. 129, No. 5, pp. 193–241 (*see* Journ. I. and S.I., 1945, No. II., p. 151 A).

Polarographic Determination of Nickel in Steel and Nickel Ore. P. W. West and J. F. Dean. (Industrial and Engineering Chemistry, Analytical Edition, 1945, vol. 17, Nov., pp. 686–688). A rapid and accurate method for determining nickel in steel and in nickel ores, based on the use of the polarograph with sodium fluoride as the supporting electrolyte, is described.

Determination of Nitrogen by Combustion. H. Gonick, D. D. Tunnicliff, E. D. Peters, L. Lykken, and V. Zahn. (Industrial and Engineering Chemistry, Analytical Edition, 1945, vol. 17, Nov., pp. 677–682). Improved apparatus and procedure are described for determining nitrogen by Dumas' combustion method.

BOOK NOTICES

(Continued from p. 56 A)

HARVEY, H. W. "*Recent Advances in the Chemistry and Biology of Sea Water.*" 8vo, pp. viii + 164. Cambridge, 1945: University Press. (Price 10*s.* 6*d.*)

A summary of the large amount of important work that has been done in recent years on the relation of plant and animal life in the sea to the chemical constituents of sea water. Much of this work has been carried out by Dr. Harvey himself and other members of the staff of the Marine Biological Laboratory at Plymouth.

MANTELL, C. L. and C. HARDY. "*Calcium Metallurgy and Technology.*" 8vo., pp. 145. Illustrated. New York, 1945: Reinhold Publishing Corporation. (Price 20*s.*)

A survey of available information on the properties, production and uses of calcium, and the constitution of the alloy systems. A chapter is devoted to the use of calcium in ferrous metallurgy.

PULL, E. "*Boiler House Practice.*" Second Edition. Sm. 8vo., pp. vi + 282. London, 1945: The Technical Press Ltd. (Price 10*s.* 6*d.*)

This book is intended as a guide to the selection, maintenance and operation of industrial steam generators and their auxiliary equipment. It also deals in a practical manner with problems relating to the efficiency of such plants.

TIBBENHAM, L. "*The Welding of Cast Iron by the Oxy-Acetylene Process.*" 2nd Edition. Sm. 8vo., pp. viii + 120. Illustrated. London, 1945: Sir Isaac Pitman and Sons Ltd. (Price 7*s.* 6*d.*)

This book deals in a practical way with every detail of the process of the oxy-acetylene welding of cast iron. Such subjects as gases employed, varieties of generator plants, composition of welding rods and fluxes, vital facts in the metallurgy of cast iron relating to welding, and methods of pre-heating are dealt with. The new process of low-temperature welding of cast iron is explained as well as bronze welding and its many uses.

MINERAL RESOURCES

(Continued from p. 37 A)

Kent Coalfield, Regional Survey Report. (Ministry of Fuel and Power, 1945 : H.M. Stationery Office).

North Eastern Coalfield, Regional Survey Report. (Ministry of Fuel and Power, 1945 : H.M. Stationery Office).

North Western Coalfields, Regional Survey Report. (Ministry of Fuel and Power, 1945 : H.M. Stationery Office).

North Midland Coalfield, Regional Survey Report. (Ministry of Fuel and Power, 1945 : H.M. Stationery Office).

The Coalfields of the Midland Region, Regional Survey Report. (Ministry of Fuel and Power, 1945 : H.M. Stationery Office).

Northumberland and Cumberland Coalfields, Regional Survey Report. (Ministry of Fuel and Power, 1945 : H.M. Stationery Office).

New Canadian Ore Deposit Has High Iron Content. (Steel, 1946, vol. 118, Feb. 25, p. 102). Brief geological details are given of a bed of hematite which has recently been discovered in the Algoma mining area to the north of Lake Huron. The ore contains about 65% of iron.

The Australian Iron and Steel Ltd. Iron Ore Undertaking at Cockatoo Island, Yampi Sound. (B.H.P. Review, 1945, vol. 23, Dec., pp. 1–3). Particulars are given of the discovery, geology, and present state of development of the iron-ore body on Cockatoo Island on the north-western coast of Western Australia. The ore is a high-grade hematite with 69% of iron. Contracts have been placed for diesel-electric power plant, electric shovels, conveyors, and quayside equipment. Living-quarters and buildings for the machinery are already being erected on the island.

Nigeria—Geology and Mineral Resources. F. Dixey. (Bulletin of the Imperial Institute, 1945, vol. 43, Oct.-Dec., pp. 300–311). A short account of the geology and mineral resources of Nigeria is given.

The Formation of Pyritiferous Iron Ores by Addition of Sulphur, and the Nature of Magnetic Pyrites. G. T. Lindroth. (Jernkontorets Annaler, 1946, vol. 130, No. 2, pp. 27–75). (In Swedish). This is the first part of a report on an investigation made in order to study the possibility of removing pyrites, especially magnetic pyrites, from concentrates of pyritiferous iron ores from the leptite system of central Sweden. The geology and crystallographic structure of the ores are dealt with in detail. An outline of the course of the reactions, probably complicated and little known, by which the sulphides were formed is given. They were probably formed by the addition of sulphur from the action of H_2S under high pressure.

French North Africa. A. H. Steedman, D. Gill, and A. Choubersky. (Ministry of Supply, Report of Minerals Division, British Economic Mission, Sept., 1945). This Report is presented by the Minerals Division of the British Economic Mission in Algiers. It contains information and views gained during a period of nearly three years' intensive work in North Africa when large quantities of phosphates and iron were purchased for shipment to the United Kingdom and the condition of the mines, transport facilities, and shipping ports of Algeria, Morocco, and Tunisia were investigated.

FUEL

(Continued from pp. 57 A–59 A)

An Electrical Analogue of the Flow of Heat in a Regenerator System. K. Heindlhofer and B. M. Larsen. (American Institute of Mining and Metallurgical Engineers, Technical Publication No. 1798 : Preprint Feb., 1945). A description is given of a relatively simple electrical apparatus which, through the close analogy between the flow of heat and of electricity, enables many complex problems of heat flow to be solved quickly and with satisfactory accuracy. Its application to solve problems relating to the design of regenerators is discussed.

The Moisture Sorption of Coals and Its Relation to Their Coking Quality. (Fuel in Science and Practice, 1946, vol. 25, Mar.-Apr., pp. 42–50). The results of experiments on the "sorptive" power of coal are related to its rank and swelling power. The steady diminution of sorptive qualities with advancing coalification may well result from the gradual reduction in number and size of the capillaries inherent in the raw material. The relation of the sorptive power of cokes to that of the parent coal is such that the hypothesis of a capillary structure affords a simple and logical picture.

Dual System for Cleaning Blast Furnace Gas. (Steel, 1946, vol. 118, Jan. 28, pp. 144–146). A brief description is given of the Dovel plant for cleaning blast-furnace gas ; it is a combination of dry and wet methods.

Some Characteristics of Blast Furnace Gas. O. R. Rice. (Iron and Steel Engineer, 1946, vol. 23, Feb., pp. 67–80). Factors affecting and affected by the quantity, calorific value, and chemical analysis of blast-furnace gas are outlined and discussed, special reference being made to the hydrogen content and to the reliable determination of the moisture in the gas. Extensive data are presented, and basic figures used by the author in calculations relating to the production, condition, and combustion of blast-furnace gas are given.

Conservation of Fuel Oil. C. R. Miller. (Iron and Steel Engineer, 1946, vol. 23, Jan., pp. 115–117). A general discussion of the use of fuel oil and methods of conserving it in industry, with data on the consumption in the United States, is presented.

A Heat-Flow Meter for Use in Furnaces. R. H. Baulk and M. W. Thring. (Iron and Steel Institute, 1946, this Journal, Section I.). The first step towards improving the flow of heat to the charge in melting furnaces is to develop an instrument to measure the value of the heat flow at any point in the furnace under the varying conditions of operation. In particular, it was desired to be able to measure the heat transfer by radiation and convection from the flame to the charge and to the furnace walls.

The work on such an instrument has reached a stage where a practical research tool has been evolved and used to compare the heating power of different flames, to examine the effect of flame thickness upon the heat flow from the flame, and to compare the heat flow at different points along and across the flame. It has shown, for example, that measurement of the downward heat flow below the flame at its two ends gives a valuable quantitative measure of the effective flame length; in the case of very slow combustion the downward heat flow at the outgoing end is greater than at the ingoing end. It has also been shown that the heat-absorbing area of the surface of the charge is not very fully utilized either in the steel furnace or in the glass tank, the former because the flame does not cover the whole area and the latter because the cold batch is not spread out.

PRODUCTION OF IRON

(Continued from pp. 59 A–60 A)

Blast Furnace Operation under Elevated Top Pressure. F. Janecek. (Iron and Steel Engineer, 1946, vol. 23, Feb., pp. 88–94, 101). The structural alterations which were made to a blast-furnace with hearth 27 ft. in dia., bosh 30 ft. in dia., and a volume of 46,230 cu. ft. above the tuyeres, to make it suitable for operating at an increased top pressure of 10 lb./sq.in. are described, and the experience gained when working at this pressure is discussed.

Blast-Furnace Theory. I. Reduction and Carburisation of Iron in the Solid State and Carbon Deposition. II. Combustion of Coal in the Hearth. III. Behaviour of Silicon and Manganese—Physical Principles. IV. Thermal Principles of the Blast-Furnace. F. Mobey. (Iron and Steel, 1945, vol. 18, Nov., pp. 481–486; Dec., pp. 629–633; 1946, vol. 19, Jan., pp. 3–6; Feb., pp. 47–51). In this series of articles the author summarizes some of the conclusions reached by a number of investigators of the blast-furnace process.

Mechanizing the Plugging of Blast-Furnace Tapholes. O. Backlund and R. Grundén. (Jernkontorets Annaler, 1946, vol. 130, No. 2, pp. 76–78). (In Swedish). The advantages of installing a clay gun for plugging blast-furnace tapholes are discussed. An increase of about 10% in the production of iron at the Herräng blast-furnaces with a decrease of 0·5% in the coke consumption was achieved.

Drains 640-Ton Salamander from Stack in an Hour. (Steel, 1946, vol. 118, Feb. 11, pp. 114–116). A description is given of the technique adopted to remove furnace bear from a blast-furnace at Indiana Harbor in 1942. A hole 8 ft. high, 6 ft. wide, and 9 ft. towards the back of the furnace was made in the foundation. Two holes 3 in. in dia. and 7 ft. deep were made from the back of the first excavation. These holes acted as guides for the oxygen lance. A 1-in. dia. line was run from a source of oxygen supply 300 ft. away; this was reduced to ½ in. in dia. and 135 ft. of ½-in. tubing was used in lancing the hole to the still molten bear. In 1 hr. 640 tons of iron were drained off and cast into 2-ton pigs in a previously prepared sand pit.

FOUNDRY PRACTICE

(Continued from pp. 60 A–61 A)

Organization of the Foundry Industry in France. V. Delport. (Foundry, 1946, vol. 74, Feb., pp. 113, 226–228). The present organization of the French foundry industry and the functions of the Office Professionnel de la Fonderie, the Centre Technique des Industries de la Fonderie, and the Association Technique de Fonderie are explained.

Foundry Uses Cupola and Direct Metal. P. Dwyer. (Foundry, 1946, vol. 74, Feb., pp. 104–107, 234–236). An illustrated account is given of the moulding and casting technique employed for making an engine-bed casting of grey iron, 26 ft. long × 11 ft. wide × 8 ft. high, weighing 100 tons.

Weather Affects Chill Depth. E. Wisbrun. (Foundry, 1946, vol. 74, Feb., pp. 109, 174–176). The effect of weather conditions on the casting properties of iron is discussed. It was noted that whilst the depth of chill was practically unaltered by a slight fall of snow at above freezing point on the raw materials, a heavy fall of snow at low temperatures considerably increased the depth of chill. The fluidity of the iron remained the same in both cases.

Controlling Gray Iron Quality. J. E. Linabury. (Gray Iron Founders' Society: Foundry, 1946, vol. 74, Feb., pp. 90, 250–254). The factors contributing to the production of good castings in grey iron are examined and recommendations for the control of quality are made.

Some Initial Results on the Influence of Tellurium as a Chill-Inducing Medium in Cast Iron. (Institute of

British Foundrymen, 1946, vol. 78, Mar. 14, pp. 283–287). Four methods of adding tellurium to cast iron were tested and the factors governing the depth of chill were investigated. Direct additions to the ladle were unsatisfactory, but enclosing the tellurium powder in copper foil or copper tubes and putting these in the cold ladle before tapping proved to be effective. With the powder in suspension in a mould-wash excellent control was obtained, as the wash could be applied to faces where no machining of the casting was necessary. Tellurium powder can also be mixed with the facing sand—a procedure which is useful for inaccessible parts of the mould where the wash cannot readily be applied.

Melting and Casting. E. F. Cone. (Materials and Methods, 1946, vol. 23, Jan., pp. 110–114). Developments in steelmaking and in processes of casting iron and steel in the United States during 1945 are reviewed. Successful results have been obtained with the all-basic open-hearth furnace. The trend towards the partial or complete mechanization of iron foundries is noted, and the application of centrifugal casting to peace-time requirements is studied.

The Age of Green and Dry Sand Molding. J. E. Hurst. (Foundry, 1946, vol. 74, Feb., pp. 97, 208–210). The history of sand moulding in Great Britain is outlined. It is known that open sand moulding was practised in Sussex in 1547. Closed sand moulds began to be used in the early part of the eighteenth century.

Mold Cavity Variation. R. Cleland, jun. (Foundry, 1946, vol. 74, Feb., pp. 91, 220–222). Factors affecting the size of the mould cavity and the extent to which it is filled by the metal are discussed. The factors dealt with are the ingredients of the moulding material, namely, moisture, fine sand, cornflour, pitch, sea coal, and clay.

Some Aspects of Green Deformation and Sand Toughness in Sand Control. W. G. Parker. (American Foundryman, 1946, vol. 9, Jan., pp. 50–54). Equipment for measuring the deformation and compressive strength of green sand by American Foundrymen's Association methods is described. When the deformation in thousandths of an inch on 2 in. is multiplied by the green compressive strength and the product is multiplied by 1000, the final product is taken as a measure of the toughness of the sand. With increasing toughness number there is usually a decrease in permeability.

Effect of Table Rise (Strain Rate) on Hot Strength of Bentonite Bonded Sands. H. W. Dietert. (American Foundryman, 1946, vol. 9, Jan., pp. 78–79). In order to obtain reproducible results in hot compressive tests on foundry sands, it is necessary that the strain rate should be specified. Tests showing the effect of different strain rates on the hot strength are discussed, and the rate of 1 in./min. is advocated.

Using Synthetic Resin Core Binders. H. L. Gebhardt. (Foundry, 1946, vol. 74, Feb., pp. 111–112, 198–206). The preparation of cores with synthetic-resin binders is discussed with data on the baking and properties of cores with the ingredients mixed in different proportions.

Pattern and Allied Equipment. W. E. Tharp. (American Foundryman, 1946, vol. 9, Jan., pp. 30–37). Recommendations on the design of patterns and on the interchangeability of patterns and other equipment are made.

Some Pattern Shop Methods and Their Advantages to the Foundry. H. W. Turner. (Institute of British Foundrymen: Foundry Trade Journal, 1946, vol. 78, Mar. 21, pp. 315–320). The preparation of patterns and the fixing of cores for small intricate castings are described.

Sand Mold Drying with Propane-Gas Torches. F. C. Rogers. (American Foundryman, 1946, vol. 9, Jan., pp. 76–77). A description is given of a propane torch which was designed for drying the surface of moulds. The torch uses compressed air at 90–105 lb./sq.in. and propane to 15–20 lb./sq.in.

Moulded Pattern Plates. J. Timbrell. (Foundry Trade Journal, 1946, vol. 78, Mar. 14, pp. 289–290). A method of making a moulded pattern plate with one master pattern and a plaster transfer block for casting a number of identical objects is described.

Casting Tuyeres in the Bethlehem Foundry. P. Dwyer. (Foundry, 1945, vol. 73, Dec., pp. 110–113, 234–236).

Employs Simple Rig for Making Blast Furnace Tuyeres. P. Dwyer. (Steel, 1946, vol. 118, Feb. 4, pp. 138–143). The technique developed by the Bethlehem Steel Company for casting bronze blast-furnace tuyeres is described and illustrated.

How to Cast Ingot Molds. P. Dwyer. (Foundry, 1946, vol. 74, Feb., pp. 158, 160). The technique for making a mould to cast ingot moulds for steel ingots measuring $3\frac{1}{2} \times 3\frac{1}{2}$ in. from 24 to 42 in. long is described.

Duplex Pump Castings. R. H. Brown. (Institute of British Foundrymen: Foundry Trade Journal, 1946, vol. 78, Feb. 28, pp. 223–233). Descriptions are given of the melting and moulding equipment and the moulding and casting technique at a jobbing foundry producing pump castings in iron and bronze.

Moulding Large Meehanite Crankshafts. G. Johnstone. (Foundry Trade Journal, 1946, vol. 78, Mar. 7, pp. 261–264). The following methods of casting large crankshafts in Meehanite cast iron are described and discussed: (1) Vertical pouring and vertical cooling; (2) horizontal pouring and vertical cooling; and (3) horizontal pouring and horizontal cooling.

Precision Casting Practice. (Steel, 1946, vol. 118, Jan. 28, pp. 116–118, 150–156; Feb. 4, pp. 129, 166–170). A detailed description of the "lost wax" process of making small and intricate castings of great accuracy in ferrous and non-ferrous metals is described (*see* Journ. I. and S.I., 1944, No. II., p. 39 A).

Shakeout Handles Large Castings. J. L. Yates. (Foundry, 1946, vol. 74, Feb., pp. 102–103, 166). An illustrated description is given of a large shake-out machine at an American foundry; it has a vibrating table with an area of 396 sq. ft., and it can deal with flasks weighing up to 75 tons.

Sealing Porous Castings. P. S. Fuller. (Engineering Materials and Processing Methods, 1945, vol. 22, Dec., pp. 1746–1750). A method of sealing micropores in castings is described. It consists of im-

pregnating the casting with a thermosetting plastic called " Laminac."

Cleanliness and Safety in the Foundry. J. Thomson. (Safety Engineering: American Foundryman, 1946, vol. 9, Jan., pp. 48–49). A powerful vacuum-cleaning unit for cleaning castings at a Chicago foundry is described and illustrated.

Foundry Ventilation. J. M. Kane. (Foundry, 1946, vol. 74, Feb., pp. 86–88, 228–233; Mar., pp. 104–108, 144–150). The problem involved in the removal of excessive heat, dust, smoke, and fumes from the foundry is analysed and ventilating equipment to meet various conditions is described and illustrated.

PRODUCTION OF STEEL

(Continued from pp. 61 A–63 A)

Restoration of Steel Plant in Southern U.S.S.R. I. Andronov. (Metallurgia, 1946, vol. 33, Feb., p. 188). An account is given of some of the rebuilding and repair work which has been completed at iron and steel works in the U.S.S.R. In the Stalino region 9 blast-furnaces, 18 open-hearth furnaces, 47 batteries of coke-ovens, and 3 Bessemer converters have been restored.

British Steel—Today and Tomorrow. E. N. Simons. (Iron and Steel Engineer, 1946, vol. 23, Feb., pp. 64–66). War-time problems in steel-making which have been overcome in Great Britain and some new processes which have been developed are reviewed. One of the latter is a method of slag control which embodies the charging of lime in furnaces using high percentages of molten phosphoric iron.

Statistical Information. (Jernkontorets Annaler, 1946, vol. 130, No. 2, pp. 81–88). (In Swedish). At a recent meeting of the Järnverksförening (Swedish Ironworks Association) a report was presented on the production, imports, and exports relating to the Swedish iron and steel industry. In this paper thirteen tables from the report are reproduced with notes on the present position of the industry.

Open Hearth Charge Ores. C. Denlinger. (Yearbook of the American Iron and Steel Institute, 1945, pp. 20–28). *See* p. 4 A.

Acid Open-Hearth Steel Making. F. S. Perry. (Sheffield Trades Technical Societies: Man and Metal, 1946, vol. 23, Mar., pp. 28–29; Apr., pp. 40–41). A description is given of an acid open-hearth steel furnace, together with a detailed account of the working of a heat.

A Study of the Durability of Steelworks Ingot Moulds. O. Hengstenberg, K. Knehans, and N. Berndt. (Iron and Steel Institute, 1946, Translation Series, No. 269). This is an English translation of a paper published in Stahl und Eisen, 1941, vol. 61, May 15, pp. 489–498, together with the discussion to which it gave rise. (*See* Journ. I. and S.I., 1941, No. II., p. 120 A).

Arc Furnaces. N. F. Dufty. (Iron and Steel, 1946, vol. 19, Mar., pp. 91–96). The design of electric arc furnaces for steelmaking and their equipment are critically reviewed. Whilst modern arc furnaces are well designed both electrically and mechanically, it is suggested that the men operating them have received too little consideration. A maximum size of 30 tons is adhered to in Great Britain, but there appear to be no logical reasons why the capacity should not be increased as has been done in the United States.

Modern Distribution Systems for Steel Mills. W. C. Bloomquist. (Iron and Steel Engineer, 1946, vol. 23, Feb., pp. 81–84, 101). The planning of a system of electricity distribution in an iron and steel works to make provision for future expansion of the plant is discussed, and the system adopted in a particular case is described.

The Removal of Hydrogen from Steel. J. H. Andrew, H. Lee, A. K. Mallik, and A. G. Quarrell. (Iron and Steel Institute, 1946, this Journal, Section I). A systematic investigation of the removal of hydrogen from a number of steels under isothermal conditions has been carried out, and it is shown that, for all steels, the rate of removal in the intermediate range is high, and that, for certain steels, there is also a peak on the removal curve corresponding to transformation in the pearlitic region. The law governing hydrogen removal in the austenitic range has been determined experimentally, and the empirical relationship supported by theoretical treatment. The effect of transformation upon the removal of hydrogen is illustrated, and the effect of specimen size is also dealt with. It is shown that small partial pressures of hydrogen surrounding the steel at 1100° C. exert a considerable retarding effect upon the removal of hydrogen, although, as might be expected, this effect becomes quite small at 650° C.

In the presence of hydrogen, the transformation of a nickel–chromium–molybdenum steel was retarded in the range 600–450° C., but little effect was observed at lower temperatures. Comparison of the rate of diffusion of hydrogen through similar specimens of different steels showed that alloying elements have little, if any, effect upon the diffusion constant. This was confirmed in the austenitic range by the results obtained for the law of hydrogen removal. The evolution of hydrogen on cooling was followed, and it was found that the maximum rate of evolution corresponded to the end of the thermal transformation.

The mechanical properties of a large number of steels have been determined after treatment in hydrogen and nitrogen, and it is shown that the embrittling effect of hydrogen is apparent in all cases where the hydrogen content is 1·0–3·0 c.c./100 g.

In connection with the work on the removal of hydrogen, much evidence has been obtained upon the formation of hair-line cracks under various conditions. It was found that such cracks could appear in the absence of transformation stresses, and that these stresses are important mainly in that they determine

the particular crack distribution which results. Although no cases were observed of internal crack formation in the absence of hydrogen, certain specimens showed no cracks in spite of a high hydrogen content. The view of the hydrogen-rich constituent put forward in a previous paper has been modified, in that it is not now considered to be necessarily austenitic; it is realized that at the moment of crack formation the steel will be in an extremely brittle condition, owing to its hydrogen content. The exact nature of the hydrogen-rich constituent cannot be given, nor can a detailed explanation of hair-line crack formation be expected, until the much wider problem of low-alloy steels in general is more thoroughly understood.

Steel Plant Is Serviced by Modern Water Works. G. E. Stedman. (Steel, 1946, vol. 118, Feb. 25, pp. 116–121). A description is given of the water-supply service at the new steelworks at Fontana, California. About 2½ million gal./day are supplied by a separate company and two 800-ft. wells have been constructed as a stand-by source of supply. A high degree of recirculation is practised owing to the lack of water in this district.

Lighting Improvements for Steel Plants. D. H. Tuck. (Iron and Steel Engineer, 1946, vol. 23, Feb., pp. 95–100). Improvements in the electric lighting equipment for steelworks which were developed in the United States during the last few years are described and discussed. Methods of measuring lighting efficiency and analysing lighting costs are explained.

FORGING, STAMPING, AND DRAWING

(Continued from p. 64 A)

Some Observations on the Design of Forged Parts. W. Naujoks. (Steel Processing, 1946, vol. 32, Jan., pp. 31–34, 42). Recommendations on the design of forged parts are made with a view to facilitating the forging operations.

Forging Die Design. J. Mueller. (Steel Processing, 1946, vol. 32, Jan., pp. 39–42). The design of dies and rolls for the gap-rolling of shaped and tapering bars is discussed. In gap-rolling, or roll-forging, the die shape takes up about half of the periphery of the rolls, and the billet or bar to be forged is inserted in the gap or recess which is left in the remaining portion of the rolls.

Developments in Production Forging. E. Simister. (Metallurgia, 1946, vol. 33, Feb., pp. 173–177). Descriptions are given of modern drop hammers, counterblow hammers, press-forging machines, and upsetters. The type of production for which each of them is suitable is explained.

Processing and Fabrication of Stainless Steel Sheet and Plate Products. H. S. Schaufus. (Steel Processing, 1946, vol. 32, Jan., pp. 43–46, 59). Data on the effect of different degrees of cold-rolling on the mechanical properties of stainless steel are presented and discussed, and the drawing, spinning, and bending of this material are considered.

Forging and Pressforming. T. C. Du Mond. (Materials and Methods, 1946, vol. 23, Jan., pp. 115–119). Advancements in the forging, press-forming, and stamping of metals in the United States during 1945 are reviewed.

Statistical Quality Control of Metal Stampings. G. R. Armstrong. (Iron Age, 1946, vol. 157, Feb. 21, pp. 46–48). The use of frequency diagrams, correlation charts, and control charts for the statistical control of the quality of metal stampings is explained.

The Witter Process for the Manufacture of Shell Forgings and the Spinning Process for the Manufacture of Bombs. J. L. Johnson. (Yearbook of the American Iron and Steel Institute, 1945, pp. 29–50). A description is given of the Witter cross-roll process of manufacturing closed-end shell forgings to the required length and thickness from a pierced blank; the cavity is so accurately finished that no machining is required. Details of a spinning process for making bombs are also given. In this case the only machining required is that for making the screwthreads on the nose and tail.

Difficulties and Developments in Deep Drawing and Pressing. J. D. Jevons. (Journal of the Institution of Production Engineers, 1946, vol. 25, Mar., pp. 67–103). The causes of "ears," strain-age-embrittlement, stretcher-strain markings, and critical strain crystal growth in deep-drawing and pressing, and methods of dealing with these difficulties are discussed.

Wax Drawing Compound. E. A. Bunting. (Steel, 1946, vol. 118, Feb. 11, pp. 88–89, 138). Details are given of the advantages of using a wax compound as a lubricant for deep-drawing steel, stainless steel, aluminium, and brass.

ROLLING-MILL PRACTICE

(Continued from pp. 64 A–65 A)

Rolling, Wire Drawing, Extruding. H. A. Knight. (Materials and Methods, 1946, vol. 23, Jan., pp. 120–122). The improvements in rolling, wire-drawing, and extruding process which were made known in the United States during 1945 are briefly reviewed. Roller bearings are tending to displace sleeve bearings in rolling-mills. The Krause and Uni-Temper types of mill are described.

Report on die Staatliche Materialprüfungsanstalt an der technische Hochschule at Cannstatterstr. 212, Stuttgart, Germany. (Combined Intelligence Objectives Sub-Committee, File No. XXV-24, 1945: H.M.

Stationery Office). A report is presented on work being done at the above Institute on addition agents to lubricants for the purpose of increasing bearing loads.

Industrial Grease Application. J. R. LeVally. (Iron and Steel Engineer, 1946, vol. 23, Feb., pp. 85–87). Modern grease guns, pumps and connectors for high-pressure lubrication systems are described and illustrated.

Light Steel Building Products. (Combined Intelligence Objectives Sub-Committee, File No. XXVI-22, 1945: H.M. Stationery Office). An account is given of the position reached in Germany in the manufacture of steel windows and doors, with details of the light sections which are rolled.

Metallurgical High Lights in the Recent Manufacture of Rolled Steel Plates and Sheets in Germany. (Combined Intelligence Objectives Sub-Committee, File No. XXVII-29, 1945: H.M. Stationery Office). Important changes which were made during the war in the manufacture of rolled steel plates and sheets in Germany are reviewed.

HEAT-TREATMENT

(Continued from pp. 65 A–66 A)

Calibration of Pit Furnaces for Airplane Propellers. C. A. Liedholm. (Metal Progress, 1946, vol. 49, Feb., pp. 361–368). A detailed description is given of two experimental heat-treatment furnaces which were designed for obtaining data to establish heat-treating specifications for hollow steel propeller blades for aircraft. The furnaces consist of refractory lined pits about 18 ft. deep. There are two interchangeable metal retorts for the high-temperature hardening furnace, and three interchangeable retorts for the low-temperature stress-relieving furnace. All the retorts are about 3 ft. 6 in. in dia., and they vary in length up to 14 ft. 6 in. to suit the size of the blades. The furnaces are heated by banks of resistance heaters in the brickwork. Equipment for the production of carburizing and protective atmospheres is available. Reports on the test runs with temperature, time, and hardness data are presented.

Heat Treating and Heating. T. C. Du Mond. (Materials and Methods, 1946, vol. 23, Jan., pp. 130–134). Achievements in the fields of heat-treating, hardening, and quenching in the United States during 1945 are reviewed.

How Heat-Treatment Affects High-Strength Irons. C. R. Austin. (Machinist, 1946, vol. 89, Feb. 2, pp. 2326–2328; Feb. 16, pp. 2404–2405). The following heat-treatments applicable to Meehanite cast iron are described: (1) Annealing for stress relief; (2) annealing for improved machinability; (3) quenching for hardness; (4) interrupted quenching; (5) martempering; (6) spheroidizing; (7) flame-hardening.

A Theory of the Mechanics of Carburization. C. R. McCloskey and J. H. Loux. (Steel Processing, 1946, vol. 32, Jan., pp. 53–56). The theory that carburization will not take place without carbon dioxide and/or water vapour being present is advanced, and evidence in support of it is put forward. When small controlled amounts of these oxidizing agents are present in the carburizing medium they oxidize the surface of the work; the oxides are immediately reduced by the overwhelming reducing potential and are activated so that they act as a catalyst in dissociating the carbon monoxide into carbon and carbon dioxide. The nascent carbon is absorbed by the activated iron on the surface forming iron carbide.

Insuring Dimensional Accuracy through Heat Treating. (Steel, 1946, vol. 118, Feb. 18, pp. 90–91, 104). The necessity for proper co-operation between the heat-treating and machining departments is emphasized, and a suitable heat-treatment to ensure dimensional accuracy in the case of a particular finished part is outlined.

Molten Baths for the Wire Industry. F. R. Morral. (Wire and Wire Products, 1945, vol. 20, Oct., pp. 736–741). The literature and patents on the application of salt baths in the wire industry for cleaning and heat-treatment are reviewed.

Handling Equipment for Heat-Treatment Furnaces. H. D. Hendrick. (Machinery, 1946, vol. 68, Mar. 14, pp. 329–333; Mar. 21, pp. 367–371). Illustrated descriptions are given of mechanical equipment for charging heat-treatment furnaces, and the design of chain and slat conveyors, pusher furnaces, and quenching equipment is considered.

Importance of a Proper Quench. J. McElgin. (Iron Age, 1946, vol. 157, Feb. 21, pp. 50–51). Experience gained in the heat-treatment of shells of 0·55%-carbon steel is described. It was found advantageous to use a stable quenching oil containing a wetting agent so that a fast rate of cooling through the critical range was obtained. To obtain satisfactory hardness, cooling oil was pumped through jets to quench the inside of the shells.

WELDING AND CUTTING

(Continued from pp. 66 A–68 A)

Metallurgical Aspects of High Quality Pressure Welded Joints for Landing Gear. Part I. Influence of Oxygen. L. Fine, C. H. Maak, and A. R. Ozanich. (Metal Progress, 1946, vol. 49, Feb., pp. 350–355). A description is given of the equipment and process for "uniwelding" steel tubes. In this process the tube ends to be butt-welded are held in alignment in a machine; the joint is surrounded by a ring-shaped burner head with a large number of orifices drilled radially in the inner surface. The head is supplied

with oxygen and acetylene and, when the tube ends have been heated to the right temperature, hydraulic pressure is applied to force the ends together. The welding time for a tube with a $\frac{1}{4}$-in. wall is about 2 min. The mechanism of the diffusion of oxygen in welds of this type is explained.

The Reconditioning of War-Damaged Machine Tools. G. Varley. (Proceedings of the Institution of Mechanical Engineers, 1945, vol. 153, War Emergency, Issue No. 4, pp. 109–111). Methods of repairing machine tools which have been damaged by bombs or fire are described and some examples are illustrated. Three methods were used : (1) Gas welding with cast-iron filler rods containing at least 3% of silicon ; (2) electric welding with covered electrodes suitable for cast iron ; and (3) bronze welding by arc using covered electrodes.

Design Considerations for Welded Machinery Parts. G. L. Snyder. (American Society of Mechanical Engineers : Metallurgia, 1946, vol. 33, Feb., pp. 183–188). **Designing Welded Machinery Parts.** G. L. Snyder. (Steel, 1946, vol. 118, Feb. 4, pp. 124–126, 162–164 ; Feb. 11, pp. 98–102, 155 ; Feb. 18, pp. 100–102, 140–144). Factors affecting the design of dynamically-loaded welded machinery parts are discussed.

High-Speed Spotwelding. B. Gross. (Iron Age, 1946, vol. 157, Feb. 21, pp. 52–55). Factors influencing high-speed spot-welding are discussed. A small apparatus for obtaining records of the time-pressure and the time-current relationships is described.

Three-Phase Distribution and Electric Welding and Furnace Loads. A. Langley Morris. (Institution of Electrical Engineers, Mar. 13, 1946). Methods of connecting single-phase welding equipment to 3-phase mains are dealt with. The single-phase transformer and the open-delta series-connected transformer are compared. Mention is made of the power-factor correction of single-phase loads, from which there has been developed a method of obtaining balanced 3-phase/single-phase conversion by static means. Full details of this phase-converting system for arc- and resistance-welding machines are given.

Notes on the Conditions of Fracture of Medium Steel Ship Plates. D. F. Windenburg and W. P. Roop. (Welding Journal, 1945, vol. 24, Nov., pp. 580-S–587-S). Tensile tests were made on notched specimens of steel ship plates measuring $24 \times 12 \times \frac{3}{4}$ in. The notch took the form of a hole through the centre ; in some cases hacksaw cuts $1\frac{3}{16}$ in. long were made in opposite sides of the hole transverse to the direction of testing. The plates were tested to rupture at various controlled temperatures and the nature of the fracture was examined. Specimens notched with a hole and hacksaw cuts broke with a brittle fracture at 75° C. whereas a similar specimen broke with a ductile fracture at 100° F. The characteristics of the fractures were not altered by sharp fatigue cracks at the ends of the saw cuts.

Report on Welding in German Shipyards. (Combined Intelligence Objectives Sub-Committee, File No. XXXII-100, 1945 : H.M. Stationery Office).

Fatigue Properties of Flash Welds. H. J. Grover, R. W. Bennett, and G. M. Foley. (Welding Journal, 1945, vol. 24, Nov., pp. 599-S–617-S). An investigation of the fatigue properties of flash-welded chromium-molybdenum steel, conducted at the Battelle Memorial Institute is described in three parts dealing respectively with welded bars, plates, and tubes. In Part I. the properties of various zones of flash-welded bars were studied by rotating-beam tests on small specimens. Part II. describes bending-fatigue tests on flash-welded plates to determine the effect of weld reinforcement. In Part III. the effect of surplus metal on the inside of the tube (" internal flash ") was tested in the rotating-beam machine.

Some Causes of Brittle Failures in Welded Mild Steel Structures. H. E. Kennedy. (Welding Journal, 1945, vol. 24, Nov., pp. 388-S–398-S). Factors affecting the formation of brittle fractures in welded steel structures were investigated by notched-bar tensile tests, bend tests, and concentrated load tests. Changes in metallurgical structure caused by temperature changes were found to be the most important factor contributing to brittle fracture. Of the measures calculated to prevent brittle fracture, post-heating to 1100° F. was found to be the best, and preheating to 400° F. or higher was very beneficial.

The Straining of Deposited Weld Metal During Cooling. E. P. De Garmo. (Welding Journal, 1945, vol. 24, Nov., pp. 561-S–563-S). An investigation of the plastic flow that takes place in a weld as the result of cooling is described. In a butt weld by the Unionmelt process, exceeding 20 in. in length, the weld metal half-way along the weld is subjected during cooling to a plastic strain greater than that corresponding to the yield point of the material.

Weldability Tests of Cast Steels. F. S. McKenna and C. E. Jackson. (Welding Journal, 1945, vol. 24, Nov., pp. 573-S–579-S). The T-bend and nick-bend tests are described and recommended as direct quantitative tests for determining the effect of changes in welding technique and heat-treatment on the ductility of cast steels, and for indicating the relative weldability of cast steels of any composition.

Oxyacetylene Cutting Tactics for Various Alloy Steels. G. V. Slottman. (Machinery, 1946, vol. 89, Mar. 16, pp. 2542–2544). Techniques for the oxyacetylene cutting of alloy steels are described. High-speed steel, high-nickel steel, stainless steels with 12–20% of chromium and 7–10% of nickel, and cast iron are difficult to cut. A reciprocating motion of the torch is required for all of these except cast iron which is cut with an oscillating motion to make a wide cut.

CLEANING AND PICKLING OF METALS

(Continued from pp. 47 A–48 A)

Sodium Hydride Descaling. W. B. Billingsley. (Canadian Metals and Metallurgical Industries, 1946, vol. 9, Jan., pp. 19–24). The sodium-hydride pickling process has been described by L. W. Townsend (*see* p. 48 A). In the present paper the full-scale plant at the works of the Rustless Iron and Steel Corporation

is described and illustrated, and the advantages of the process are pointed out.

Three Examples of Modern Practice in the Recovery of Waste Pickling Liquors. P. De Lattre. (Sheet Metal Industries, 1946, vol. 23, Feb., pp. 282–286, 288). Descriptions are given of three pickling plants belonging to a tube manufacturing company in Belgium. At two of these plants the spent liquor is treated as a whole, which involves the use of rather large deposit and settling tanks. In the third, where high-precision tubes are made, a continuous regeneration plant has been installed eliminating entirely the need for settling and deposit tanks.

The Chemistry and Mechanism of Steel Pickling. B. N. Reavell. (Institute of Vitreous Enamellers: Sheet Metal Industries, 1946, vol. 23, Feb., pp. 323–326). The mechanism of pickling is explained on the basis of electrochemical rather than chemical reactions. The following nett equations may be taken to summarize the reactions involved :

$$Fe_3O_4 + Fe + 4H_2SO_4 = 4FeSO_4 + 4H_2O$$
$$Fe_3O_4 + Fe + 8HCl = 4FeCl_2 + 4H_2O.$$

As long as scale remains in contact with the base metal, then, in the presence of the electrolyte, innumerable electrolytic cells of the types $Fe–Fe_2O_3$, $Fe–FeO–Fe_3O_4$, $Fe–Fe_3O_4–Fe_2O_3$ are set up; these lead to a reduction of some of the oxides to a ferrous state which reacts with the acid ions to form ferrous salts which pass into solution.

Batch and continuous plants are briefly described with notes on acid neutralization and acid recovery.

The Effect of Various Surface Treatments in Cleaning and Preparing Copper, Nickel, and Steel for Chromium Plating. W. T. Tucker and R. L. Flint. (Electrochemical Society, Oct., 1945, Preprint No. 28). The Hull cell was utilized as a device for studying the reluctance of certain cathodes to accept a chromium deposit. Results of excellent reproducibility were obtained. It was concluded that the commercial methods of surface preparation evolved since the inception of chromium plating were adequate if certain limiting factors were duly considered. Neither copper nor steel were found to be acutely sensitive to methods of surface preparation.

Pickling of Sheet Steel prior to Vitreous Porcelain Enamelling. F. Stanley. (Australasian Engineer, 1946, Jan. 7, pp. 64–69). Detailed recommendations on pickling procedure for steel sheet which is to be vitreous-enamelled are made and formulæ for the rapid calculation of acid additions are presented. " Pickle pill " and titration methods of bath control are described.

Cleaning and De-Whiskering Nails. A. J. Lehman. (Steel, 1946, vol. 118, Feb. 18, pp. 123–126). In the nail-manufacturing process the nails come from the dies coated with a mixture of lime and soap, and there is also a small " rag " of metal left at the point by the knives. A new process for removing both coating and rag is described. The nails are tumbled in a hot solution and sawdust is used only to dry and burnish the clean nails. The continuous unit has automatic charging and discharging devices.

COATING OF METALS

(Continued from pp. 48 A–50 A)

Metallic Coating by Immersion. E. Dupuy. (Revue de Métallurgie, Mémoires, 1944, vol. 41, July, pp. 208–216). The author discusses the use of various metals, such as tin, zinc, copper, lead, cadmium, and aluminium, for coatings for one of the following purposes: (1) To modify the external appearance; (2) to resist corrosion; (3) to facilitate cold-working; and (4) for welding and soldering. A brief description is given of immersion methods of coating with tin, zinc, lead, cadmium, and aluminium.

Precision Seamless Tubing by Electrodeposition. J. Albin. (Iron Age, 1946, vol. 157, Jan. 10, pp. 54–58). Some details of the Ekko process of plating iron have been given in an earlier publication (*see* Journ. I. and S.I., 1940, No. I., p. 155 A). In this article particulars are given of the application of the process to the manufacture, with a high degree of accuracy, of seamless tubes of irregular shape.

The Electrodeposition of Nickel-Cobalt-Tungsten Alloys from an Acid Plating Bath. P. F. Hoglund and M. L. Holt. (Electrochemical Society, Oct., 1945, Preprint No. 24). The electrodeposition of nickel-cobalt-tungsten alloys from an aqueous plating bath is reported. The most satisfactory bath was found to be a modified Fink and Lah borate-type of nickel-cobalt bath to which was added a small amount of sodium tungstate.

Wire Galvanizing—Herman Process. R. Hussey. (Wire and Wire Products, 1945, vol. 20, Dec., pp. 927–931). A description is given of the Herman hot-dip process for galvanizing wire. In this process there is a small auxiliary zinc pot at the exit end of the main pot. The wires are drawn up through a slot-shaped nozzle, 10 in. high, through which molten zinc is circulated. Above the nozzle there is a chamber of about 6 cu. ft. which is kept full of natural gas. The wires pass up through the gas and are cooled in a stream of water directed across them.

The Formation of Dross in Hot-Dip Galvanizing. P. M. Fisk and F. F. Pollak. (Sheet Metal Industries, 1946, vol. 23, Mar., pp. 490–492, 494). The effect of changes in the pickling and washing conditions on the amount of free iron in mg./sq.m. produced on specimens of steel plate $4\frac{1}{2} \times 1\frac{3}{4}$ in. was investigated. As 3 lb. of iron produce 100 lb. of dross in the subsequent hot-dip galvanizing process, the data obtained are important in studying methods of reducing dross formation. The amount of free iron increased rapidly with increasing roughness of surface and with the quantity of iron in the pickle solution. Steel pickled in cold hydrochloric acid is not freed from iron salts under ordinary production conditions after dipping in static water as easily as the steel pickled in sulphuric acid.

The Electrodeposition of Tin-Zinc Alloys. R. M. Angles. (Journal of the Electrodepositors' Technical Society, 1946, vol. 21, pp. 45–64). The results of an investigation on the deposition of tin-zinc alloys, ranging in composition from 92/8 to 28/72, are discussed, and the procedure for depositing the alloy containing 78% of tin, which appears to be the most serviceable, is given.

The Protective Value of Lead and Lead-Tin Deposits on Steel. A. H. Du Rose. (Electrochemical Society, Oct., 1945, Preprint No. 7). The effects of the thickness of the deposit and of the concentration and nature of the addition agents to the plating bath on the protective value of lead and lead-tin coatings on steel were investigated. An increase in the glue concentration in the lead fluoborate plating solution gives better covering and throwing power. Lead deposits give a surprisingly good protection to steel against corrosion. A lead-tin alloy deposit containing 5–6% of tin gives better protection than either pure lead or an alloy higher in tin.

Metallizing in Welding Fabrication. W. J. Brooking. (Canadian Metals and Metallurgical Industries, 1946, vol. 9, Jan., pp. 14–18, 24). The application of metal-spraying for the repair of worn shafts, hubs, and bushes, as well as for the salvage of over-machined parts, is described and illustrated.

The Application of Cold Metal Spraying. V. G. Young. (Diesel Engine Users' Association : Australasian Engineer, 1946, Jan. 7, pp. 61–62). The advantages and limitations of the metal-spraying process for the repair of diesel engine parts are discussed.

Electrical Testing of Wire, etc. (Wire Industry, 1946, vol. 13, Feb., pp. 103–105). Descriptions are given of an enamelled wire pin-hole tester and a magnetic sorting bridge. The former instrument counts the number of flaws and pin-holes of a given maximum resistance in a length of enamelled wire. The sorting bridge enables samples of any ferromagnetic materials to be tested and determinations made of differences in their composition, hardness, temper, and electrical conductivity.

Conveyorized Enamelling of Castings. H. Chase. (Iron Age, 1946, vol. 157, Feb. 14, pp. 53–55). A description is given of a highly mechanized plant at which cast and stamped components are cleaned, bonderized, sprayed, and baked on a continuous chain conveyor with specially designed controls.

The Decoration of Blackplate and Tinplate. T. A. Miller. (Sheet Metal Industries, 1946, vol. 23, Feb., pp. 291–292, 298). Recent developments in the sizing, lacquering, and printing for the decoration of blackplate and tinplate are reviewed, and some future possibilities discussed.

Synthetic Coatings for Gasoline Tanks. (Combined Intelligence Objectives Sub-Committee, File No. XXX-67, 1945 : H.M. Stationery Office). A brief report on German methods of applying synthetic coatings on the inside of tanks used for storing petrol is presented. For small tanks, baked phenol-formaldehyde resin coatings were used, whereas for larger tanks a plasticized nitrocellulose air-dried lacquer was applied. This lacquer, however, was modified by the addition of soluble urea-formaldehyde resin which was cured by the addition of phosphoric acid to effect good adhesion and to render the film insoluble in petrol.

Plastic Skin Protective Coatings Convert to Peace-Time Applications. B. Gould. (Corrosion and Material Protection, 1946, vol. 3, Feb., pp. 6–9, 12). Some particulars are given of a plastic coating with a cellulose acetate butyrate base into which steel parts can be dipped. A bath kept at 300–340° F. is used and, on withdrawing the part, the solution solidifies leaving a transparent film completely impervious to moisture.

PROPERTIES AND TESTS

(Continued from pp. 68 A–69 A)

Young's Modulus—Its Metallurgical Aspects. D. J. Mack. (American Institute of Mining and Metallurgical Engineers, Technical Publication No. 1936 : Metals Technology, 1945, vol. 12, Dec.). The literature on Young's modulus is critically reviewed, and a number of empirical relations correlating the modulus with other properties such as atomic volume and specific heat are considered ; the best is considered to be that of J. P. Andrews. The bibliography contains 103 references.

Correlation of Inspection Methods in the Metal Industry. J. V. Rigbey. (Canadian Metals and Metallurgical Industries, 1945, vol. 8, Nov., pp. 36–40 ; Dec., pp. 38–41, 48–52). Modern methods of testing and inspecting metals are reviewed and their significance is discussed.

Sulphur—Effects in Cast Iron and Steel. E. S. Brown. (Sheffield Trades Technical Societies : Iron and Steel, 1946, vol. 19, Feb., pp. 71–74). The effects of sulphur on the properties of cast iron and steel are discussed, and data on the reduction in tensile properties of steel at high temperatures with increasing sulphur content are presented. Some experiments on desulphurization with soda ash are described ; the conclusions derived from them are : (1) The amount of soda ash used should be related to the initial sulphur contents ; (2) it is uneconomical to make additions of more than 22½ lb. of soda ash per ton of steel ; and (3) a double treatment is essential when an initial sulphur content exceeding 0·090% is to be brought down to 0·010–0·020%.

Shot-Peening. (Aircraft Production, 1945, vol. 7, Oct., pp. 478–480). The characteristics of the shot used for shot-peening and data on the increase in fatigue strength obtained by peening wire are discussed. A method of checking the depth to which the peening affects the steel is described.

The Hardenability Concept. J. H. Hollomon and L. D. Jaffe. (American Institute of Mining and Metallurgical Engineers, Technical Publication No.

1926: Metals Technology, 1946, vol. 13, Jan.). Experimental determinations of the hardenabilities of some high-alloy steels compared with the hardenability calculated by the Grossmann system have indicated that the calculated hardenabilities are too high. The Grossmann system and the whole concept of hardenability are therefore examined in this paper. In order to determine the effects of the alloying elements on the bainitic hardenability, the alloying elements should be added to the steels in which bainite limits the formation of martensite. This occurs in the case of steels containing about 0·25% of molybdenum. Since no carefully planned experiments of this type have been performed, a tentative system is suggested as an interim measure to permit very rough estimates of the bainitic hardenability to be made. Hardenabilities calculated by this system for a number of steels have been found to check well with the measured hardenabilities. One of the conclusions based on the results of isothermal experiments in this tentative system is that molybdenum and the grain size of the austenite have little, if any, effect on the rate of bainite formation.

Hardenability and Quench Cracking. L. D. Jaffe and J. H. Hollomon. (American Institute of Mining and Metallurgical Engineers, Technical Publication No. 1927: Metals Technology, 1946, vol. 13, Jan.). A method is suggested for selecting the composition of alloy steels which will have a specified hardenability with a minimum quench-cracking tendency.

Progress Report on Hardenability Bands. (Yearbook of the American Iron and Steel Institute, 1945, pp. 51–84). This Report was prepared by the Technical Committee on Alloy Steel of the American Iron and Steel Institute. It deals with the advantages and disadvantages of specifying alloy steels by hardenability instead of by analysis. The production records for the principal alloy steels manufactured in a period of two months in the United States show that 14% of the open-hearth heats and 4·4% of the electric-furnace heats were outside of the specified limits of analysis. Frequency curves for the contents of various elements in these "off" heats are presented and discussed. The general conclusion is that it would be both practicable and advantageous to widen the present limits of specified contents of elements and to specify hardenability limits based on Jominy end-quench tests.

Hardenability. A. Portevin. (Revue de Métallurgie, Mémoires, 1944, vol. 41, July, pp. 193–203; Aug., pp. 243–248). The author discusses the theoretical and practical aspects of hardenability of steel and cast iron. Methods of testing hardenability are described and the value and application of the results obtained are explained.

New Developments in Hardness Testing. V. E. Lysaght. (Metallurgia, 1946, vol. 33, Feb., pp. 210–212). The Knoop hardness-testing indenter, the Tukon tester for applying light loads with the Knoop indenter, and some work carried out with them are described.

Applications of Eberbach Microhardness Tester. H. E. Bernhardt. (Steel, 1946, vol. 118, Feb. 25, pp. 92–100, 140). The Eberbach microhardness

testing instrument is described. It operates with a spring-loaded diamond indenter of similar shape to that in the Vickers machine. Results obtained with it are presented and compared with those obtained by other methods.

The Value of the Impact Test in the Study of Temper Brittleness. H. Jolivet and G. Vidal. (Revue de Métallurgie, Mémoires, 1944, vol. 41, Nov., pp. 378–388; Dec., pp. 403–408). The results of impact tests on specimens from eleven heats of 1·3–2·0%-chromium 0·26%-molybdenum 0·23%-vanadium steel are presented. Mesnager notched specimens subjected to various heat-treatments were used. The influence of the deformation velocity, temperature, notch shape, and heat-treatment were investigated. Temper brittleness can be detected only by measuring the impact strength when the test is carried out under favourable conditions.

The Physical Nature and Properties of Modern Magnet Steels and the Practical Design and Testing of Permanent Magnets. E. Spahn. (Schweizer Archiv, 1944, vol. 10, Oct., pp. 313–322).

Testing and Inspection. H. A. Knight. (Materials and Methods, 1946, vol. 23, Jan., pp. 145–150). The methods of testing and inspection which are reviewed in this paper include electronic measurements, spectrography, magnetic inspection, hardness testing with light loads, strain gauge determinations, the measurement of surface roughness, and radiography.

Other Non-Destructive Methods of Testing. J. W. Juppenlatz. (American Foundryman, 1946, vol. 9, Jan., pp. 38–41). Non-destructive methods of testing castings other than radiography and magnetic particle testing are described and discussed. These include: (*a*) Washing the surface with a fluorescent penetrating liquid and subsequent examination under ultra-violet light; (*b*) static loading tests in which the deflection is measured; (*c*) air-pressure and liquid-pressure tests; and (*d*) supersonic tests.

Crack Inspection. F. W. Giles. (Engineering Inspection, 1945, vol. 10, Winter Issue, pp. 22–26). Methods of detecting cracks in metals are briefly reviewed. Each method has a particular merit against the others in a given circumstance and experience proves that there is room for them all.

Electronic Testing. (Iron and Steel, 1946, vol. 19, Mar., pp. 119–120). Electronic instruments for comparing the mechanical characteristics of great numbers of parts, for detecting cracks, and for determining the thickness of non-magnetic coatings on steel are described.

Metallic Creep. (Engineer, 1946, vol. 181, Feb. 15, pp. 148–149; Feb. 22, pp. 170–171). **Creep of Metals.** (Engineering, 1946, vol. 161, Mar. 8, pp. 233–235; Mar. 15, pp. 258–259). A brief report is presented of the proceedings at a conference on metallic creep which was held in London on February 5, 1946. It was organized by the Department of Scientific and Industrial Research and about 150 representatives of research establishments, universities, and industrial organizations were present.

A Comparison of Some Carbon Steels on the Basis of Various Creep Limits. A. E. Johnson and H. J. Tapsell. (Proceedings of the Institution of Mechanical

Engineers, 1945, vol. 153, War Emergency Issue No. 6, pp. 169–179). This paper describes work done to determine whether any relationship exists between the results of the various short-time and long-time creep tests, which will permit the use of short-time tests, not merely as a means of separating good from bad steels, but also as the basis of design stresses intended to give satisfactory performance over working periods of considerable duration. Indications are given of some of the difficulties and limitations in the use of short-time creep results in the case of carbon steels, and suggestions are made for some rational basis for steps which might be taken to offset these difficulties and limitations by applying the results of short-time tests to the estimation of design stresses.

Creep Properties of Steels Utilized in High-Pressure and High-Temperature Superheater and Steam Pipe Practice. Part II. 0·5 Per Cent Molybdenum Steels. H. J. Tapsell and R. W. Ridley. (Report J/T 136 of the British Electrical and Allied Industries Research Association: Proceedings of the Institution of Mechanical Engineers, 1945, vol. 153, War Emergency Issue No. 6, pp. 181–192). This report deals with the creep properties of carbon-molybdenum steels in the form of a superheater header, superheater tube, and steam pipe manufactured for service at temperatures above 450° C. The investigation was carried out in a similar manner to that described in Part I. (*see* Journ. I. and S.I., 1944, No. II., p. 88 A), which dealt with carbon steels and, as in the former case, the object was to obtain data for the estimation of the stress-temperature relationships for from 0·1 to 0·5% creep in various periods up to 100,000 hr. It is considered that the data provide a satisfactory basis for design.

Valve Facing Alloy Resists Corrosion at High Temperatures. V. C. Young. (Engineering Materials and Processing Methods, 1945, vol. 22, Dec., pp. 1744–1745). Some particulars are given of the properties of an alloy called "Eatonite," containing chromium, nickel, tungsten, and cobalt, which maintains a high hardness at red heat, and is used for facing the valves of aero-engines.

16-25-6 Alloy for Gas Turbines. M. Fleischmann. (Iron Age, 1946, vol. 157, Jan. 17, pp. 44–53; Jan. 24, pp. 50–60). A comprehensive account is given of the development by the Timken Roller Bearing Company of a 16/25/6 chromium-nickel-molybdenum steel for use at high temperature in gas turbines. Details are given of its microstructure, heat-treatment, and room-temperature and high-temperature properties.

The Influence of Heat-Treatment and Micro-Structure of Austenitic Heat-Resisting Steels on the Scatter of Creep-Test Results. E. Morlet. (Revue de Métallurgie, Mémoires, 1944, vol. 41, June, pp. 161–168; Sept., pp. 284–291; Oct., pp. 346–352). The author presents a report on a study of creep resistance; it is in three parts which deal with: (1) Creep-testing machines and the accuracy of the measurements; (2) the influence of heat-treatment; and (3) the influence of the grain size on creep tests of short and long duration. Creep tests were made at 650°, 750°, and 850° C. on an 18/8 austenitic chromium-nickel steel with an addition of 3·5–4·0% of tungsten, and on an austenitic-ferritic 24/12 chromium-nickel steel. The effect of heat-treatment and of different grain sizes on the creep resistance, creep rate, and scatter of the results was examined. The following conclusions were arrived at: (1) In order to limit the scatter of the creep-test results, the heat-treatment should be carried out at the following temperatures: Quenching from 1150° C. followed by tempering at 900° C. for 6 hr. (2) A coarse-grained steel possesses a higher creep resistance, and it is possible to represent by a diagram on a logarithmic scale the variation of the creep rate in relation to the number of grains per square millimetre. (3) The scatter of the results is more pronounced in creep tests of long duration, and this shows the superiority of coarse-grained forged steel over a fine-grained rolled steel. (4) The coarse grain, caused by overheating, makes the steel susceptible to intergranular fractures which considerably affect the creep resistance.

Report on Metals for Elevated Temperatures. (Combined Intelligence Objectives Sub-Committee: File No. XXXII-99, 1945: H.M. Stationery Office). Information is given on German methods of creep-testing, their alloy steels for boilers, and on the Krupp heat-resisting steels.

Report on Materials for Shipbuilding Applications. (Combined Intelligence Objectives Sub-Committee, File No. XXXII-105, 1945: H.M. Stationery Office).

The Diffusion of Hydrogen Through Iron at Room Temperature. J. H. De Boer and J. D. Fast. (Recueil des Travaux Chimiques des Pays-Bas, 1939, vol. 58, Sept.-Oct., pp. 984–993). When iron sheets are brought into contact with aqueous solutions of definite *p*H values, diffusion of hydrogen through the iron takes place in all cases where the liquid dissolves iron with the evolution of hydrogen. No diffusion takes place if the *p*H value of the liquid is such that there is no evolution of nascent hydrogen. This proves that atoms of hydrogen formed by the chemical reaction may enter the iron, whilst the hydrogen ions contained in the solutions are unable to do so. In accordance with these results it was found that hydrogen atoms formed in hydrogen gas by means of an incandescent tungsten coil readily enter iron plates at room temperature. An iron vessel filled with hydrogen can be evacuated in this way. As hydrogen can diffuse only through the iron from the side where atoms are produced, it accumulates on the other side of the iron wall and diffusion takes place against an atmosphere of hydrogen at any pressure.

A Test for Hydrogen Embrittlement and Its Application to 17 per Cent Chromium, 1 per Cent Carbon Stainless-Steel Wire. C. A. Zapffe and M. Eleanor Haslem. (American Institute of Mining and Metallurgical Engineers, Technical Publication No. 1954: Metals Technology, 1946, vol. 13, Jan.). An apparatus is described with which hydrogen embrittlement in wire can be measured as a function of the angle at which breaking occurs during a single bend made at constant speed. This simple instrument is used first to get an approximate indication of the sensitivity of various grades of stainless steel wire to hydrogen embrittlement and then to study factors controlling the absorption of hydrogen during cathodic and acid pickling and the evolution of that gas during subse-

quent recovery. After establishing the fundamental relationships of charging time, temperature, and current density, it was found that many inhibitors, often advertised as inhibiting or preventing hydrogen embrittlement, actually caused a marked increase in embrittlement when compared with the acid bath without such additions. Only two reagents, neither of which was a commercial product, were found to be true inhibitors at certain concentrations; at other concentrations they, too, aggravated embrittlement. The peculiarities of a group of these reagents were studied in detail. During the recovery period the specimens first decreased in ductility, a very marked spontaneous embrittlement being observed. As an example of the effect of temperature on the rate of recovery, it was noted that, after 40 sec. at 180° C., the recovery was the same as after 71 hr. at 0° C. The evidence obtained in these tests supported the "planar-pressure" theory of hydrogen embrittlement.

Steels and Irons. F. P. Peters. (Materials and Methods, 1946, vol. 23, Jan., pp. 86–89). Some of the ferrous materials developed during 1945 are reviewed with notes on their properties. They include alloys for use at high temperature, high-ductility steels for forming, boron-bearing malleable cast iron, "H" steels with specified limits of hardenability, steels with special magnetic properties, and tool steels.

Railway Rails. M. Cambournac. (Revue de Métallurgie, Mémoires, 1944, vol. 41, Aug., pp. 233–242; Sept., pp. 301–312). The author presents the results of the investigations made by a special Commission for Rails in France, whose task was to examine the causes of various defects and to suggest means of eliminating them.

Some Interesting Properties of Titanium Steels. G. F. Comstock. (Journal of the American Ceramic Society, 1946, vol. 29, Jan., pp. 1–7). Steel containing sufficient titanium to combine with all of the carbon does not react with vitreous enamels like ordinary low-carbon steel or ingot iron; white cover-coat enamels, without a ground coat, can therefore be fused on it without blistering or the formation of black specks. The titanium content must be more than $4\frac{1}{2}$ times the carbon content. This steel has been made commercially by the basic open-hearth process, and the requirements for successful manufacture are explained. It is of excellent quality for deep-drawing and does not have a yield point, even when normalized or annealed, so that stretcher-strains cannot occur in it. It is not subject to strain-ageing even when strained as much as 17% and aged at 450° F.

Steel Wool—Characteristics of Materials and Manufacture. L. E. Browne. (Steel, 1946, vol. 118, Feb. 25, pp. 87, 124). The manufacture of steel wool is described and its properties discussed. Hot-rolled steel (containing about 0·12% of carbon and 0·90% of manganese) $\frac{7}{32}$ in. in dia. is drawn down to 0·01 in. wire, and the fine strands for making into wool are shaved off the wire with a serrated-edged tool which removes several strands at a time. The strands are made in seven sizes between 0·0018 in. and 0·0080 in. in dia. The binding of the strands into wool is not described.

Ferrous Metallurgical Research. N. A. Matthews. (Journal of Applied Physics, 1945, vol. 16, Dec., pp. 780–787). The organization, equipment, and work being done at the Watertown Arsenal Laboratory, Massachusetts, are described and discussed.

A Workable Classification of Toolsteels. C. L. Hibert. (Metal Progress, 1946, vol. 49, Feb., pp. 333–341). The method of coding tool steels adopted by the Consolidated Vultee Aircraft Corporation is described. The steels were divided into five major groups with 14 sub-divisions. The groups, each of which with its own distinctive mark, are: (1) General-purpose tool steels; (2) oil-hardening die steels; (3) silicon-manganese shock-resisting chisel and punch steels; (4) high-carbon high-chromium punch and die steels; and (5) high-speed tool steels.

Nomenclature and Standards. (Jernkontorets Annaler, 1946, vol. 130, No. 2, pp. 79–80). (In Swedish). The *Tekniska Nomenklaturcentral* (Bureau for Technical Nomenclature) is about to publish a list of 200 definitions and terms relating to the strength of materials, which have been agreed upon by a committee of fifteen Swedish scientists and industrialists. A short review of some of the definitions is given and comments are invited.

METALLOGRAPHY AND CONSTITUTION

(Continued from pp. 69 A–70 A)

A Temper-Etching Process for Distinguishing between Ferrite, Austenite, and Carbides in the Structure of High-Chromium Steels. H. Kessner. (Iron and Steel Institute, 1946, Translation Series, No. 270). This is an English translation of a paper which was published in Archiv für das Eisenhüttenwesen, 1942, vol. 16, Oct., pp. 145–146. (*See* p. 15 A).

Industry's Debt to Röntgen. G. L. Clark. (Industrial Radiography, 1945, vol. 4, Winter Issue, pp. 30–34, 49). The development of the use of X-rays for industrial purposes during the last fifty years is outlined.

Some Questions that Can be Answered by X-Ray Diffraction. C. S. Barrett. (Industrial Radiography, 1945, vol. 4, Winter Issue, pp. 12–18). A general survey of the field covered by X-ray diffraction is presented. Its application to obtain data for constructing phase diagrams and studying the effects of deforming and heat-treating metals is dealt with.

Atomic Structure of Steels. Audrey M. B. Parker. (Steel, 1946, vol. 118, Feb. 25, pp. 89, 127). The Debye and Scherrer method of obtaining X-ray powder photographs is described and their significance in studying the atomic structure of steels is explained.

Technique and the Future of Industrial Radiography. M. B. Evans. (Industrial Radiography, 1945, vol. 4, Winter Issue, pp. 19–22). War-time improvements in X-ray technique are reviewed and

an assessment is made of their value in application to peace-time requirements.

Ultra High Speed Radiography. E. R. Thilo. (Industrial Radiography, 1945, vol. 4, Winter Issue, pp. 40–43). The technique for obtaining high-speed X-ray photographs is described with examples of its use for studying the penetration of plates by bullets and other ballistical problems.

Two Million Volt X-Ray Inspection Equipment. D. Goodman. (Metal Progress, 1946, vol. 49, Feb., pp. 327–332).

High-Voltage Radiography. D. Goodman. (Iron Age, 1946, vol. 157, Feb. 21, pp. 58–61). Experience gained from the use of 1,000,000-V. and 2,000,000-V. X-ray equipment in the United States is reported. The latter size of equipment weighs about 5000 lb. and measures 5 ft. in dia. and 11 ft. in length; with it, a radiograph can be taken through steel 12 in. thick at a distance of 3 ft. with an exposure of 2 hr.

Application of X-Ray Analysis to Metallurgy. M. Païc. (Revue de Métallurgie, Mémoires, 1944, vol. 41, June, pp. 169–179). The author discusses the method of quantitative micro-analysis which is based on the absorption of X-rays passing through a substance. He investigates the loss of intensity of X-rays when penetrating various metals, and shows on a diagram the relationship between the absorption and atomic number of various elements. The practical application of this law is shown by several examples.

Report on Radiography and Magnetic Inspection in German Shipyards. (Combined Intelligence Objectives Sub-Committee, File No. XXXII-102, 1945: H.M. Stationery Office).

Microstructure Related to Properties of Cast Iron. W. E. Mahin and H. W. Lownie, jun. (American Foundryman, 1946, vol. 9, Jan., pp. 20–28). Explanations of the terms cementite, ferrite, pearlite, and steadite are given and the manner in which these constituents and graphite affect the properties of cast iron is explained.

Introduction to a Study of Coalescence in Eutectoid and Hypereutectoid Steels. N. T. Belaiew. (Revue de Métallurgie, Mémoires, 1944, vol. 41, Mar., pp. 65–70; Apr., pp. 122–130; May, pp. 150–158; June, pp. 188–191; July, pp. 227–232; Aug., pp. 249–257; Sept., pp. 292–300; Oct., pp. 341–345). A comprehensive study is presented on the influence of carbides on the quality of steel. The importance of three main factors is discussed; those factors are the size, form, and distribution of the carbides. The author's general conclusions are: (1) The quantity, distribution, form, and size of the carbides exert a profound influence on the properties of steel. In the first place, the elastic limit, hardness, and impact strength are directly affected. Secondly, as the hardening penetration depends on the size of the carbides, the complex properties, such as hardenability and machinability, are also affected. (2) In order to determine the size of the carbides a formula similar to that used for the definition of grain size is applied. The formula is $M = 2^N$ (where M is the number of particles in thousands/sq.cm. and N is the dispersion. The dispersion N and hardness remain in a straight-line relationship which is shown in a dispersion/Brinell-hardness diagram. (3) The mechanism of the tempering of martensite, from the point of view of the morphology of cementite, is revealed by a growth of the cementite spheroids with time and temperature. (4) The lamellar structures are essentially unstable and tend to become spheroids. In the course of this evolution each lamella contracts into grains the diameter of which, at the end of the period of the complete disintegration, is 15 to 16 times the width of the lamella. (5) The evolution of pearlite into a globular form is very slow and is effected by annealing. (6) The coarse carbides act, similarly to other inclusions, as nuclei for crystallization; they affect the structure and quality of steel by influencing its hardenability. They impede the grain growth, at the same time preventing overheating, and they reduce the hardenability. On the other hand, the fine carbides easily enter into solution and their presence is indispensable to obtain the hardening effect in steel after quenching. (7) The coarse carbides in the hypereutectoid carbon steels increase their cutting ability and produce the same effect as the complex cementites in the high-speed tool steels. (8) Recent investigations on grain size and hardenability, which are properties closely connected with the distribution, form, and size of carbides, made it possible in many cases to replace high-alloy steels with plain carbon steels.

Some Factors Affecting Edgewise Growth of Pearlite. W. H. Brandt. (American Institute of Mining and Metallurgical Engineers, Technical Publication No. 1857: Metals Technology, 1945, vol. 12, Dec.). In an earlier paper (*see* Journ. I. and S.I., 1945, No. II., p. 97 A) the author presented a method for calculating V, the velocity of the edgewise growth of pearlite, using linear extrapolations of the ferrite and cementite solubilities. Whilst the results were in fairly good agreement with the experimental data, the calculated velocity of growth at 600° C. was, contrary to expectation, smaller than G (the velocity of radial growth of pearlite nodules). In this paper the calculation is repeated using a new extrapolation for the ferrite solubility. A calculation is also made of the effect of the carbon content on the value of V. The problem of calculating the effects of other alloying elements on rates of growth is also dealt with.

Equilibrium Relations in Medium-Alloy Steels. C. Zener. (American Institute of Mining and Metallurgical Engineers, Technical Publication No. 1856: Metals Technology, 1946, vol. 13, Jan.). The general theory for the equilibrium between two solid phases is developed from thermodynamic and mechanical concepts. This general theory is applied to the equilibrium relationships between the α, γ, and cementite phases of the iron–carbon system, and to the effects of alloying elements thereon. Experimentally obtained data on equilibria are brought into a consistent picture and a method is developed for rapidly computing the equilibrium relationships in any medium-alloy steel.

Phase Boundaries in Medium-Alloy Steels. W. A. West. (American Institute of Mining and Metallurgical Engineers, Technical Publication No. 1924:

Metals Technology, 1946, vol. 13, Jan.). Equations have been developed by Zener (*see* preceding abstract) which permit the calculation of phase boundaries in medium-alloy steels in terms of certain constants. In this paper experimental data from the literature have been used to determine the constants for a number of alloying elements and these have been compared with the constants obtained by Zener's equations. Two systems have been found which do not conform with Zener's theory; in certain others the data were inconclusive or insufficient; in a considerable number, however, constants may be chosen that represent the experimental results reasonably closely.

Kinetics of the Decomposition of Austenite. C. Zener. (American Institute of Mining and Metallurgical Engineers, Technical Publication No. 1925: Metals Technology, 1946, vol. 13, Jan.). A review is made of the general principles that govern the phenomena accompanying the decomposition of austenite; these include nucleation, propagation of interfaces, grain growth, and spheroidization. The main features of pearlite formation can be derived directly from fundamental principles. The formation of bainite is interpreted as a transformation of the face-centred austenite lattice to the body-centred ferrite lattice without a change in carbon distribution. Martensite is interpreted as having essentially the same structure as untempered bainite, except that, owing to its mode of formation, residual stresses are present. The manner in which alloying elements affect the formation of martensite is found to be such that, when arranged in the order in which they lower the Ar″ point, the order is the same as when arranged according to effectiveness in retarding the bainite transformation. The transformation of martensite from a tetragonal lattice to a cubic lattice is interpreted as a change from an ordered distribution of carbon to a random distribution.

BOOK NOTICES

(Continued from p. 71 A)

Bennett, H. "*Substitutes.*" 8vo, pp. x + 225. Brooklyn, N.Y., 1943: Chemical Publishing Co., Inc. (Price 21*s.*)

A handbook of substitutes and alternatives for chemicals, metals, fibres, and other commercial products, including a plan for choosing proper substitutes.

Boston, O. W. "*A Bibliography on Cutting of Metals 1864–1943.*" 8vo, pp. xi + 547. New York, 1945: American Society of Mechanical Engineers. (Price 39*s.*)

Professor Boston has already prepared two volumes of references—one published as a Research Bulletin of the A.S.M.E. in 1930, and a second one published personally by him in 1935. The present volume consists of the material published in the two previous volumes, together with nearly 3500 additional references with abstracts; it forms the most complete bibliography of the literature on the cutting of metals.

Drinker, P., and T. Hatch. "*Industrial Dust. Hygienic Significance, Measurement, and Control.*" 8vo, pp. viii + 316. Illustrated. New York, 1936: McGraw-Hill Book Co., Inc.; London: McGraw-Hill Publishing Co., Ltd. (Price 24*s.*)

This book, which is written from the engineer's standpoint, contains the following chapters: (1) Physical properties of dusts, fumes, and mists; (2) Effects of dusts and fumes upon man; (3) Physical and chemical factors in pneumoconiosis; (4) Permissible dustiness; (5) The dust survey; (6) and (7) Dust determination; (8) Determination of particle size; (9) Chemical and minerological analyses; (10) Control of the dust hazard—General; (11) Design of local exhaust systems; (12) Air-cleaning apparatus; (13) Air-cleaning apparatus—Filtration; (14) Dust respirators and air masks.

Evans, E. A. "*Lubricating and Allied Oils.*" Foreword by the late Viscount Wakefield of Hythe. Third edition, revised. 8vo, pp. ix + 210. Illustrated. London, 1945: Chapman and Hall, Ltd. (Price 15*s.*)

This new edition has been almost completely rewritten, whilst its original scope and outlook have been preserved. Several new chapters have been added which, it is hoped, will increase the usefulness of the book. Fatty oils have been described in a way which should give chemists a better appreciation of their constitution and behaviour. The question of engine deposits is also discussed and an introductory survey made of the new subject of chemical addition agents.

Hall, J. J. "*Steel Hardening, Tempering, and Annealing.*" Sm. 8vo, pp. 160. Illustrated. London, 1945: George Newnes, Ltd. (Price 6*s.*)

This book, which gives a concise account of the theory and practice of the heat-treatment of steel, is intended for tool hardeners, mechanics, and others interested in the manufacture and maintenance of cutting tools, dies, and other engineering components requiring heat-treatment.

Jarvis, E. G., and H. O. Jarvis. "*Facts for Foundrymen.*" Sm. 8vo, pp. ix + 80. Buffalo, N.Y., 1944: Niagara Falls Smelting and Refining Corporation. (Price $1.00.)

This small book outlines the properties and uses of the most commonly used metals and alloys. The information is presented for the foundryman to assist him in the production of better castings.

May, E. C. "*Principio to Wheeling 1715–1945. A Pageant of Iron and Steel.*" 8vo, pp. xiv + 335. New York and London, 1945: Harper and Brothers. (Price 15*s.*)

This volume traces the evolution of a colonial iron furnace at Principio, Maryland, into the huge blast-furnace, open-hearth, and rolling-mill plant at Wheeling, West Virginia, and describes the present-day activities of the Wheeling Steel Corporation.

National Research Council. "*Chemistry of Coal Utilization.*" H. H. Lowry, Editor. 8vo. Vol. 1, pp. cv + 920. Vol. 2, pp. cv + 921–1868. Illustrated. New York, 1945: John Wiley and Sons, Inc.; London: Chapman and Hall, Ltd. (Price £6 the 2 volumes.)

This treatise constitutes a comprehensive and critical review of the voluminous but scattered literature on the

scientific and practical aspects of coal utilization. In many cases hitherto unpublished data have been included. The material is presented in two volumes.

Vol. I. comprises 24 chapters covering, among other subjects, the origin of coal; its classification; its petrography; its calorific value; its hardness, strength, and grindability; its general physical properties; its chemical constitution; the fusion, flow, and clinkering of coal ash; the cleaning of coal; changes that take place in coal on storage; the action of solvents on coal; vacuum distillation of coal; coal carbonization; and coke.

Vol. II. comprises 16 chapters dealing with such subjects as the recovery of sulphur and nitrogenous compounds from coal gas; light oil from coke-oven gas; removal of miscellaneous constituents from coal gas; utilization of coal gas; the chemical nature of coal tar; ammoniacal liquor; combustion; direct generation of electricity from coal and gas; water gas; hydrogenation of coal and tar; synthesis of hydrocarbons and of methanol from water gas.

Reich, H. J. "*Principles of Electron Tubes.*" 8vo, pp. xv + 398. Illustrated. New York, 1941: McGraw-Hill Book Co., Inc.; London: McGraw-Hill Publishing Co., Ltd. (Price 21*s.*)

This book has been specially prepared to meet the needs of students who do not intend to specialize in communication. It is an abridgement of a previous work entitled "Theory and Applications of Electron Tubes."

Stewart, F. S. "*Airframe Materials.*" 8vo, pp. x + 237. Illustrated. New York, 1945: McGraw-Hill Book Co., Inc.; London: McGraw-Hill Publishing Co., Ltd. (Price 15*s.*)

It contains the following chapters: (1) The sources of strength of materials; (2) Properties of materials and methods of testing for quality; (3) Comparison of certain physical and mechanical properties of airframe materials; (4) Heat-treatment of aluminium alloys; (5) Heat-treatment of steel, magnesium, and other materials; (6) Effect of cold-working on the properties of aluminium alloys; bending limitation of wood, plastics, and magnesium; (7) Corrosion of metals and ageing of plastics; (8) Cleaning and chemical treatment; (9) Bonding processes used to join materials structurally; (10) Casting and forging of aluminium and magnesium; other metals; (11) Veneers and plywood. Adhesives; (12) Sealing processes used in airplanes; problems involved; (13) Plastic compositions; (14) Transparent plastics.

BIBLIOGRAPHY

(Continued from p. 36 A)

American Society for Metals. "*A.S.M. Review of Current Metal Literature.*" Pp. 800. Cleveland, Ohio, 1945: The Society. (Price $15.00.)

American Society for Testing Materials. "*Symposium on Magnetic Particle Testing.*" Philadelphia, 1945: The Society. (Price $1.25.)

Armstrong, E. F., and L. M. Miall. "*Raw Materials from the Sea.*" Pp. 164. Leicester: Constructive Publications. (Price 15*s.*)

British Standards Institution. STA 5. "*Schedule of Carbon and Alloy Steels. V. Steels. Bars, Billets, Forgings, Plates, Sections, Sheets, Strip, Wire, Tubes.*" 4to, pp. 103. London, 1945: The Institution. (Price 7*s.* 6*d.*)

Gabor, D. "*The Electron Microscope.*" Pp. 104. London: Hulton Press, Ltd. (Price 4*s.* 6*d.*)

Hall, N., and G. B. Hogaboom, jun. "*Dictionary of Metal-Finishing Chemicals.*" Pp. 129. New York, 1945: Metal Industry Publishing Co. (Price $3.00.)

Hemsley, S. H. "*Optical Instruments in Engineering.*" Pp. viii + 80. London: Paul Elek, Ltd. (Price 7*s.* 6*d.*)

Johnson, C. G. "*Metallurgy.*" Second edition. Pp. 262. Chicago: American Technical Society. (Price $2.50.)

Juncos, I. R. "*Experiencias sobre variacion de la textura microscópica de los metales durante el ensayo de tracción.*" Pp. 34. Rosario, Argentina, 1944: Ministerio de justicia e instrucción publica.

"*Kingzett's Chemical Encyclopædia.*" Seventh Edition, revised and edited by R. K. Strong. 8vo, pp. viii + 1092. London: Baillière, Tindall and Cox. (Price 45*s.*)

Landau, D. "*Wear of Metals.*" Second Edition. Pp. 85. New York: The Nitralloy Corporation.

Lea, F. C., and E. N. Simons. "*The Machining of Steel Simply Explained.*" London: Blackie and Son, Ltd. (Price 8*s.* 6*d.*)

Mawhinney, M. H. "*The Heating of Steel.*" Pp. 265. New York: Reinhold Publishing Corp. (Price $4.75.)

Michel, A. "*Aciers à Outils.*" 8vo, pp. 246. Illustrated. Paris, 1944: Dunod. (Price 245 *frs.*)

Ritchey, J. "*Pattern Making.*" Revised by W. W. Monroe, C. W. Beese, and P. R. Hall. Pp. 233. Chicago: American Technical Society. (Price $2.00.)

Walker, R. C. "*Electronic Equipment and Accessories; Principles of Electronics and their Applications in Industry.*" Pp. 401. Brooklyn, N.Y.: Chemical Publishing Co. (Price $6.00.)

SUBJECT INDEX.

[References to the papers read before the Institute are indicated by the word *Paper* following the page number. The letter *P.* denotes a reference in Section I. of the Journal which contains the reports of the proceedings of meetings, the papers read, and the discussions thereon. The letter *A.* denotes a reference to the section dealing with abstracts.

Indexing of Alloy Steels and Other Alloys. In the indexing of alloy steels, carbon and iron are ignored and the alloying elements contained in the steel are arranged in alphabetical order; for example all references to nickel-chromium-molybdenum steel will be found under the heading chromium-molybdenum-nickel steel. In the indexing of other alloys, carbon and iron, when present, are included in the title; iron, when present, is always mentioned first and the other elements follow in alphabetical order, carbon being in all cases mentioned last. Examples: "Iron-silicon-carbon alloys" and "iron-chromium-nickel-carbon alloys."]

NAME INDEX.

Printed in Great Britain by Richard Clay and Company, Ltd., Bungay, Suffolk.